Prediction and control of road traffic noise associated with non-free flowing vehicular traffic

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PREDICTION AND CONTROL OF ROAD TRAFFIC NOISE ASSOCIATED WITH NON-FREE FLOWING VEHICULAR TRAFFIC

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SUMMARY

The work reported in this thesis deals with prediction and control of road transport noise in urban and suburban areas, where the flow of traffic is non-free. While there is slow progress in minimising vehicle noise at source, it is increasingly important to have adequate methods of noise prediction, so as to control it by means of design and planning. The research for this thesis was necessary because the inevitable problem of traffic noise in built-up environments has not been matched by reliable prediction methods to assess its effects. The relevance of the study is borne out by current efforts to impose motor vehicle noise emission standards, traffic noise exposure regulations and by the greater public awareness of traffic noise, at national and international levels. Two main areas have been covered: (1) evaluation of the most appropriate means of traffic noise control, including the lack of previous practice (Chapters 2-4), and (2) establishment of new prediction models for various design and planning purposes, to include noise along with the traditional economic and geometric factors, based on a wide range of physical and social surveys (Chapters 5-9).

Noise from non-free flowing traffic has not previously been modelled satisfactorily, due to the large number of contributory variables. Earlier prediction methods which resulted mainly in regression or computer models showed several performance limitations such as: neglect of design elements (e.g L_{eq}, speed, junction and facade); and large error margin. There is also insufficient knowledge of people response to noise.

To develop models which could be used with confidence, a systematic investigation of interrelated topics was undertaken through a comprehensive programme of field study. A technique for data collecting and analysis was established and a pilot study carried out. The main study eventually considered all the noise indices and independent variables (basic and descriptive) required by designers and planners at different levels.

Initially the relationship between noise level and urban variables was appraised in some detail. The best empirically derived regression models were found between noise, L_{10} dB(A), and the 'basic variables' combined in the vicinity of roundabouts, traffic light intersections and priority junctions. L_{eq} was also found to be significant. The new prediction models, which evaluate noise level at each type of junction in terms of three classes of vehicles, speed, road width, location of junctions, and nearside building facade, were highly accurate. They also proved that the situation can be modelled although little has been issued in this field.

By gathering comprehensive real-life data, new overall prediction models were established, in terms of L_{10}, L_{50}, L_{90} and L_{eq}, and based on traffic composition, various kinds of junctions, farside and nearside facades and speed for urban conditions where the speed limit is below 48 Km/h. Other models for urban and suburban conditions where the speed limit is between 10-75 Km/h were also established, with variation in some elements. A model which related L_{eq} to L_{10}, L_{50} and L_{90} was also introduced. The influence on noise by building shielding and elevation was examined. The L_{10} and L_{eq} models, based on the familiar 'basic variables', were proved superior to the previous methods. They are suitable for rapid assessment and early planning and design stages.

People responses to noise and its contributing factors have been investigated by examination of the answers to the questionnaire which considered various aspects of noise annoyance. This also included development of the Overall Traffic Noise Annoyance Index (OTNAI), as a scale for assessing the effects of noise. New prediction models were then issued relating OTNAI to noise exposure indices L_{10}, L_{50} and L_{eq} dB(A). The OTNAI models represent adequate and comprehensive means for planning and design objectives.

The difficulty of covering all the related variables mathematically necessitated the establishment of a new computer model to assess and predict road transport noise and annoyance under a variety of urban and suburban conditions. Apart from the 'basic variables', the model also considered the 'descriptive variables' (e.g land use). The model covered almost all the variables of a built-up environment. It gives predicted L_{10}, L_{50}, L_{90}, L_{eq} and OTNAI, and other characteristics of each measurement site. The model is an efficient tool for thorough and detailed schemes. A new graphic computer model was also developed to maintain the recommended noise level, under various conditions, by modifying the individual variables.

In their application to practical situations, and superiority over the previous methods, the prediction models of this thesis are shown to provide an effective methodology for the execution of traffic noise control policy in built-up contexts, during the processes of transportation planning, road building, traffic management, urban planning and building construction.

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Principal Symbols

d	Distance between nearside kerb and nearside building facade (m)
dB(A)	The A-weighted decibel (A unit of sound level)
df	degree of freedom
E	Residual (measured-predicted values)
f	f - distribution
F	Distance between measurement point and farside building facade (m)
H	Number of heavy vehicles (v/h), i.e all commercial vehicles with 3 or more axles
HI	Height of measurement point (m)
J	Distance between measurement point and considered junction (m)
K	Distance between measurement point and nearside kerb (m)
L	Number of light vehicles (v/h), i.e cars, car based vans and 2 axle commercial vehicles with an unladen weight less than or equal to 3000 Kg
L_{10}	The sound level exceeded for 10% of some stated time
L_{50}	The sound level exceeded for 50% of some stated time
L_{90}	The sound level exceeded for 90% of some stated time
L_{eq}	The equivalent sound level
M	Number of medium vehicles (v/h), i.e commercial vehicles with 2 axles and an unladen weight exceeding 3000 Kg, including buses and coaches
MS	Mean square

N	Distance between measurement point and nearside building facade (m)
O	Office area
OS	Open space area
OTNAI	Overall Traffic Noise Annoyance Index
P	Percentage of medium and heavy vehicles (%)
PJ	Priority junction
Q	Traffic flow (v/h)
R	Correlation coefficient
RB	Roundabout
RS	Residential area
S	Shopping area
SPR	Suburban principal route area
SR	Site reference
SS	Sum square
t	t - distribution
TL	Traffic light intersection
UMR	Urban main road area
V	Speed of traffic (Km/h)
VR	Variance ratio
W	Road width (m)

CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 THE TRAFFIC NOISE PROBLEM

Road transport has always been, and continues to be, an essential ingredient of the progress of civilisation. During the last few decades, the rapid increase of motor vehicle use and ownership together with population growth and the attraction of people into urban and suburban regions for work or leisure, has set in motion developments that have led to a modern society in which traffic noise appears to be an inevitable problem. This noise is now predominant world-wide and will continue to be a major problem in the future (OECD, 1980). Thus, a great public awareness of road transport noise has resulted in greater efforts to minimise its effects.

Social surveys in several countries have indicated that more people are annoyed by traffic noise than by any other source of noise pollution. In Great Britain the problem of traffic noise was recognised by the Wilson Committee (Wilson, 1963) and its observations were related to a central London survey in 1961/1962. In that survey, it was estimated that noise from vehicles was predominant at 84% of the sites. This pattern exists in all urban areas and there is no indication that the situation has improved (Vulkan, 1985). In the USA, highway traffic noise affects 40% of the population (Harris, Cohn and Bowlby, 1985), while in West Germany 40% of the population feel very, or continuously, annoyed by the noise (Kemper, 1985). Rathe (1984, 1985) estimates that in Europe about 50 million people are exposed to levels of about L_{eq} = 65 dB(A) and over 200 million to more than 55 dB(A), while the OECD member countries comprised about 130 million people who were exposed to mean daily levels of more than L_{eq} = 65 dB(A) in 1984 (the recommended maximum level in residential areas is L_{eq} = 60 dB(A), section 4.5). The effects of road traffic noise on public health are evident (Croome, 1977; US Environmental Protection Agency, 1978). This is particularly true of noise in built-up areas, which accompanies people in their daily activity outdoors and at home. People's response to road traffic noise is shown in several ways such as the physiological effects, the effects on activities and the psychosociological effects (OECD, 1980).

When considering the design or introduction of road schemes, it is usual to measure the benefits in terms of traditional engineering and economic parameters, e.g. the forecasts of the flow expected in the design year, and time saving (Duff, 1974; Plowden, 1985). The environmental effects of traffic always came a poor third to the traditional parameters and there was no way of ensuring that they were given fair consideration in the planning and design processes. During the last twenty years the greater public awareness of the disadvantages of vehicular traffic has drawn attention to increasingly complex problems of wide interest. So the importance of traffic noise as one of the parameters for planners, building and road designers and traffic engineers has increased tremendously. In Britain, for example, the published 1978 White Paper (Department of Transport, 1978) placed emphasis upon the importance of environmental effects. Paragraph 48 included that 'it is more necessary now to design schemes so as to minimise the damage to communities and the environment, and roads in future will be built more for environmental than for economic reasons alone'. In addition, where a new road is being installed or an existing one modified, a statutory limit is set for noise exposure at dwellings (House of Commons, 1975). Above this limit the householder is entitled to compensation in the form of improved noise insulation in the house (see Section 4.5).

City engineers and planners are, therefore, faced with the prospect of the increasing use of vehicles despite the deterioration of the environment. They have to balance the benefits of motor vehicles with their environmental effects. They must be in a position, firstly, to consider in depth the relationship between existing road traffic and its environment. Secondly, they must predict the future environmental influences of traffic demand during the planning process when the locations of roads and building or other noise sensitive areas are being decided upon. Thirdly, they need to evaluate alternative plans in terms of safety and comfort for the public.

The above have served to increase the importance of noise prediction methods as tools for minimising the 'unwanted sound'. The main approach is to use them during the design and planning operations in place of field measurements. The advantages are those of a saving of time and money. Prediction methods also give the decision-maker freedom to modify any variables in order to create the best system. Furthermore, it is convenient to have a prediction tool which relies on existing transportation engineering methods (see Chapter 4).

Various types of forecasting methods have been utilised up until now. Most of these methods have been established to assist in the consideration of noise from high speed and free flowing traffic (Department of the Environment, 1975; Kugler, Commins and Galloway, 1976). In contrast, the increasing importance of noise effects in built-up areas under non-free flowing traffic conditions has not been matched by a similar development of comprehensive reliable prediction methods which assess its significance. This mode of traffic flow is usually interrupted by junctions and occurs in areas of complex conditions which result in changeable noise levels. The interaction between the large number of related variables associated with this situation is the main reason for the lack of reliable prediction methods.

Previous prediction methods for noise of non-free flowing traffic gave rise to regression or computer models, but these show several limitations (see Chapter 4). Thus, there are still many questions to be answered in this field before a completely satisfactory method for predicting and evaluating is evolved. This study is an attempt to investigate environmental noise such as this.

1.2 THE OBJECTIVES OF THIS RESEARCH

When dealing with noise and its control three components usually need to be considered: first, the source of the noise; second, the path along which the noise travels; third, the receiver. In the case of traffic noise in urban and suburban areas the source is various kinds of vehicles, travelling at different speeds and conditions through areas of various types of land use. The transmission path is the direction taken by the sound waves. The receiver may be any subject who works or lives in the area. There are three possible means of attack for abatement of traffic noise levels. The best method of course is to reduce the generation of vehicle noise at source. But this option is not one over which the planners and city engineers have control. Besides, there has been slow progress in this area during the years because it is dependent on complex factors (see Chapter 2).

The alternative methods therefore involve attenuating of the sound wave along its path from source to receiver and minimising the effectiveness of the penetration at the receiving point.

This study is concerned with the last two methods of noise control. The objective was to investigate the problems of road transport noise at restricted points in the traffic flow caused by signalised intersections, roundabouts and priority junctions in various urban and suburban conditions. Fig. 1.1 shows elements of traffic noise control in built-up areas.

In view of the limited prior field data regarding principal variables, and the need for a reliable prediction methods, as well as the incomplete knowledge of the various relationships between traffic noise and people responses, the main approaches to the above objective may be summarised as follows:

(1) A review of the present state of the art in order to appraise the level of progress and see to what degree it can help in the development of this research (Chapters 2, 3 and 4).

(2) The establishment of a methodology for studying the noise levels and collecting the required field data (Chapter 5).

(3) Interpretation of the field data in terms of variables that modify the noise abatement (Chapter 5).

(4) Evaluation of as many variables as possible. These should formalise the structure of the environment and are commonly considered in the planning and design operations (Chapters 5 and 6).

(5) The development of prediction models that adequately enable the effects of a wide range of variables on noise levels to be considered, and give accurate and practical results (Chapter 7).

(6) The appraisal of public reactions to road traffic noise and to the variables of a built-up environment in order to estimate the extent of the problem of noise (Chapter 8).

(7) Formulation of prediction models for traffic noise annoyance in built-up situations (Chapter 8).

(8) Formulation of a comprehensive computer model in terms of overall variables of interest (Chapter 9).

(9) Formulation of a graphic computer model to estimate the noise levels by modifying the individual variables under different conditions (Chapter 9).

Fig 1.2 shows a flow chart of planning experimental procedures of this study. A number of papers have been published on this work. These are listed in Appendix D.

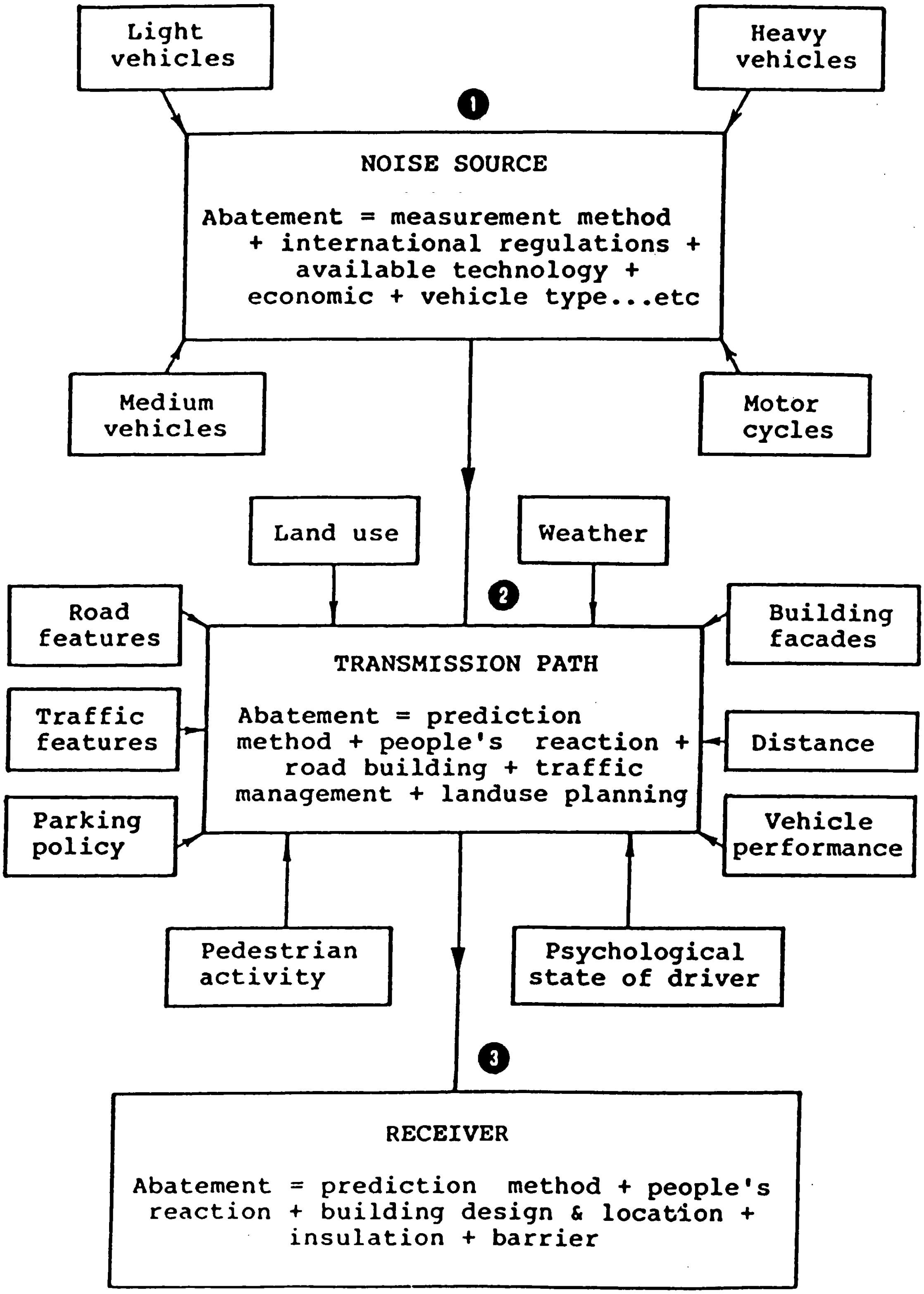
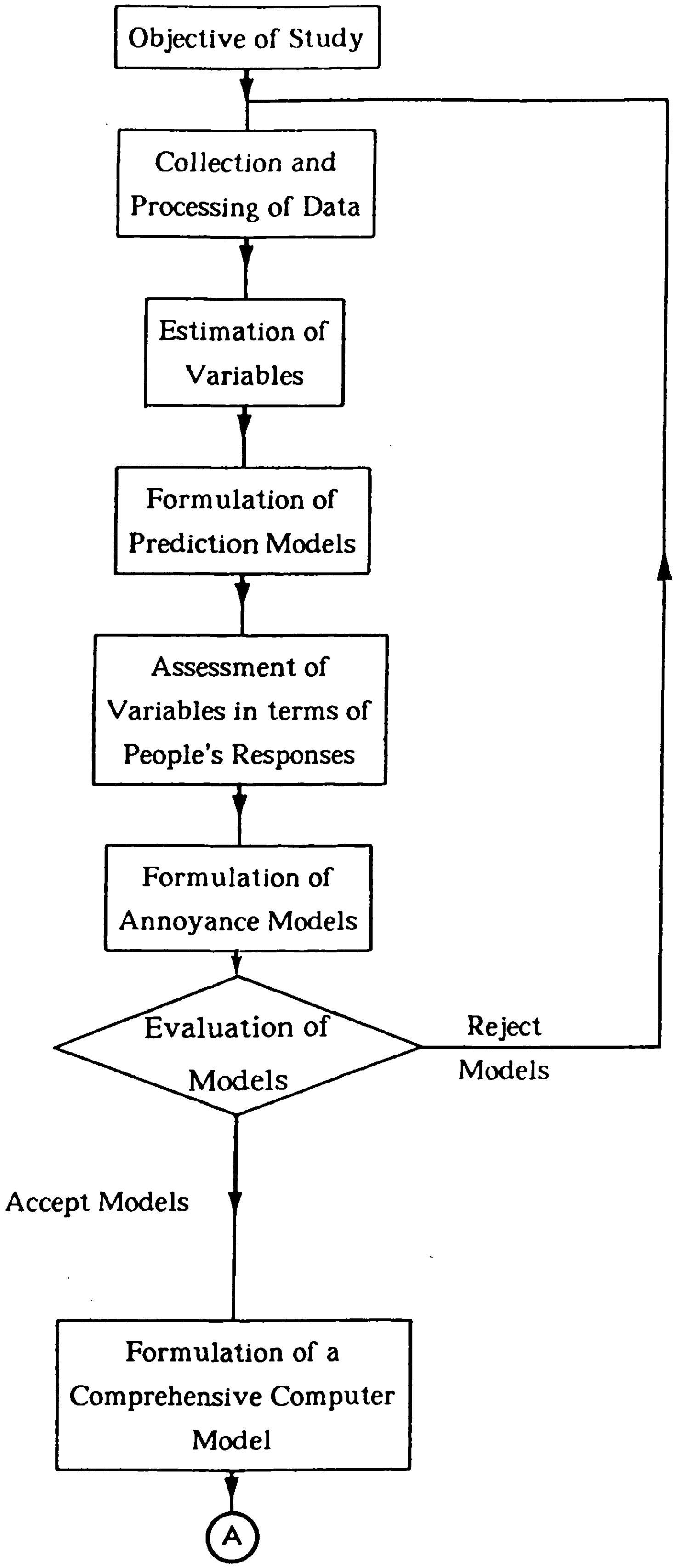


Fig 1.1 Elements of traffic noise control in built-up areas


Objective of Study
Collection and Processing of Data
Estimation of Variables
Formulation of Prediction Models
Assessment of Variables in terms of People's Responses
Formulation of Annoyance Models
Evaluation of Models
Reject Models
Accept Models
Formulation of a Comprehensive Computer Model
A

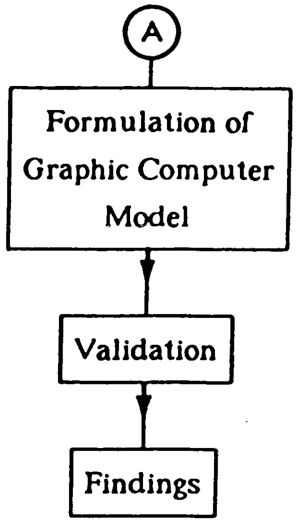


Fig 1.2 Flow chart of planning experimental procedures of this study

PART ONE

BRIEF REVIEW OF CURRENT ROAD TRAFFIC NOISE PRACTICE

CHAPTER TWO

MOTOR VEHICLE NOISE IDENTIFICATION AND POTENTIAL ABATEMENT

2.1 INTRODUCTION

The principal source of traffic noise in urban and suburban areas (built-up areas)is large numbers of vehicles. These vehicles normally have a number of prominent noise sources. Each source's characteristics are related to the operating conditions of the vehicle in a different way. The combination of these sources from many vehicles, moving at changeable speed through various road configurations surrounded by buildings with different uses, produce traffic noise. It is beyond doubt that reducing the motor vehicle noise sources is one of the effective ways to control noise. But this option is subject to many complex factors which are responsible for the slow development of this field during the past years.

This chapter deals with the various noise-generating components of vehicles which are the main cause of noise emission. It contains the following information:

(1) Sources of individual vehicle noise.
(2) Total vehicle noise.
(3) Evaluation of present vehicle noise control.
(4) Source abatement forecast.

The main task to which this study was directed is to estimate the existing research knowledge and assess to what degree it can aid in the development of a legitimate method of minimising the environmental aspects of road transport noise.

2.2 SOURCES OF INDIVIDUAL VEHICLE NOISE

The noise from an individual vehicle is a function of the design characteristics of the vehicle, the way in which the vehicle is being driven and the design and location of the road on which the vehicle operates. A road vehicle is continuously subjected to different performing conditions and it is very seldom that steady-state running occurs over a period of any length (Priede, 1980). The main operating parameters are speed, acceleration and deceleration, with associated gear changes.

Analysis of individual vehicles as a source of noise has shown that the vehicles primarily responsible for urban road traffic noise (Nelson and Piner 1977) can be divided into 3 groups. Firstly, light vehicles, which include cars, car-based vans and two axle commercial vehicles with an unladen weight less than or equal to 3000 Kg. Secondly, medium heavy vehicles, which include commercial vehicles with two axles and an unladen weight exceeding 3000 Kg as well as buses and coaches. Thirdly, heavy vehicles, which include all commercial vehicles with three or more axles. The first group is the quietest, and the third is the noisiest.

The noise of the road vehicle comes from a number of individual sources. The resultant noise from these sources may have very complex characteristics (Priede, 1980). In general, the origins of motor vehicle noise fall into two distinct categories, firstly, power system noise which usually relates to engine speed, and secondly, coasting noise which relates to road speed. The noise from the power system is mainly generated by the engine, the fan and that part of the gearbox which rotates at the engine speed. Also included in this category are various engine accessories such as air compressors, hydraulic pumps and electrical generators. The most important contributions from the engine are provided by the exhaust, noise directly radiated from the cylinder block and noise from intake. Noise from coasting originates from tyre/road contact, wind and sometimes from transmission (VDA, 1978). Fig. 2.1 shows the typical sources of motor vehicle noise.

The importance of these different sound sources in terms of the total vehicle noise depends to a differing degree on operating conditions, e.g. driving manner. Their order also varies from vehicle type to vehicle type and does not apply to heavy vehicles in the same way as to private cars. For example, diesel-powered lorries add a significant dimension to the traffic noise problem in contrast with petrol ones. Diesel engines are operated most of the time at full speed and maximum power - unlike passenger cars (Priede, 1975, 1980). At low speed and in interrupted traffic flow, power system noise (e.g. engine) is the main source of noise, while tyre and road interaction contribute to noise in high-speed, freely flowing traffic.

There is still not much information available on the noise reductions obtained from the various sources on the vehicle when they are modified individually. The main reason is that the legal requirements treat the vehicle as a whole to achieve specific noise limits. This procedure leads to the loss of much knowledge about individual source behaviour. Another reason is the difficulty of isolating each source. However, the participation of these noise generators depends on the maximum produced dB(A) noise level. Thus, the noise of major sources must be reduced to minimise the total vehicle noise. In the following discussion the vehicles' individual sources and their control are described briefly.

2.2.1 Engine noise

In road vehicles, the engine surfaces, affected by combustion and mechanical noise, produce a high noise level. Engine noise is usually dependent on its rotational speed and the vehicle load. Priede (1962) concluded that the main sources of noise in the internal combustion engine are due to the combustion and are dependent on the form of pressure rise. It was confirmed also that the predominant noise from diesel engines is produced by the rapid rise in cylinder pressure following combustion (Road Research Laboratory, 1970). This noise is added to the secondary mechanical sources of noise (e.g. fuel ignition systems and pistons) to produce the total noise level. The engine load can produce an increase in noise level, as can poor maintenance, particularly on heavy goods vehicles. Engine size also affects noise emission (Priede, 1980).

It has been found by different researchers that the noise of an engine increases linearly with the logarithm of the rotational speed. The slope of this linear relation depends on the kind of engine, and empirical equations of varying slope values have been established (Road Research Laboratory, 1970). Engine noise, like other vehicle sources, is best specified by the A- Weighted dB level. However, engine noise is more important at the low vehicle speeds associated with an urban environment.

Reduction of engine noise is always a complex task and is the subject of continuing research in industrial countries (Transportation Research Board, 1975). It involves either modification of the engine, or use of enclosure. An example that involves the reduction of diesel engine noise suggests the use of the following methods (Bugliarello, Alexandre, Barnes and Wakstein, 1976):

(1) Choice of engine design parameters. For example, for a given horse power, a quieter engine is obtained by the choice of a large number of cylinders of smaller bore.
(2) Control of noise due to combustion, e.g. modifying injection arrangements.

(3) Cover design, e.g. 60% of the external surface of an engine consists of casings or covers. If the cover noise can be completely eliminated, the overall engine noise can be reduced.

(4) Engine shielding and enclosure have been found to give a useful reduction of noise.

However, design work on engines and shielding an engine for noise reduction results in an increase of the weight which, in turn, marginally increases fuel consumption and exhaust levels. Also, shielding an engine will lead to inadequate cooling. Furthermore, any technique for reducing engine noise levels usually results in increased vehicle cost. At the present time there is no perfect method available for worldwide use but there have been successful trials in some countries (Rathe, 1984).

2.2.2 Intake and exhaust noise

Engine intake noise on a normal internal combustion engine is generated by the opening and the closing of the inlet valve. The noise spectrum is affected by the flow properties of the exhaust valve and exhaust system (Road Research Laboratory, 1970). It often increases with increasing load, and has a linear relation with the logarithm of engine speed.

Exhaust noise is similar in nature to intake noise. It is produced by the sudden release of gas into the exhaust system following the opening of the exhaust valves, and is related, like intake noise, linearly to the logarithm of engine speed.

Intake and exhaust noises are predominant in an internal combustion engine. With stop-start activity of vehicles in built up areas, this kind of noise becomes a major disturbance item.

The most effective means of controlling these noises depends on the use of silencers which reduce the induced pressure fluctuations (Raff and Perry, 1973; Alexandre, Lamure and Langdon, 1975). This reduction generally depends on the silencer type and the engine for which it is to be used.

2.2.3 Cooling system

The main sources of noise in a vehicle's cooling system are normally the fan, noise from the water pump, belts, water flow within the cooling system, and air flow through the radiator (Road Research Laboratory, 1970).

The most common type of engine cooling fan is the axial flow type, usually drawing air through the radiator in water-cooled engines. Centrifugal fans may be used with air cooled engines. The fan produces a noise which increases with the increase of speed of engine rotation. When the vehicle maneuvers at low speed the level of fan noise is increased.

Several possible approaches to fan noise reduction are available. Consideration of the design of the fan itself can improve its aerodynamic characteristics. Improved air flow through the fan can be obtained by removal of obstructions or by placing it in an acoustically treated duct. Replacing one large fan by two smaller ones on a large power system can also provide a reduction in overall noise (Raff and Perry 1973; Alexandre *etal*., 1975).

2.2.4 Transmission noise

Little is known about the mechanism of transmission noise production (Bugliarello *etal*., 1976). It is believed that it originates from the radiation of engine vibration and by vibratory forces caused by the gear mechanism.

The inclusion of the gearbox in any engine enclosure is likely to lead to further noise reduction (Road Research Laboratory, 1970; Raff and Perry 1973). The fitting of automatic transmissions also resulted in an average reduction in the noise level of about 2-4 dB(A) (VDA, 1978).

2.2.5 Wind noise

It was found that externally generated wind noise is not important relative to other noise sources, until the speed exceeds 100 km/h for lorries and 130 km/h for passenger cars (Nilsson and Sandberg, 1982). There is no available study which might indicate the effect of wind at low speed.

2.2.6 Tyre-Road noise

One of the major components of vehicle noise is that caused by the interaction of the vehicle tyres with the road surface. Tyre-road noise is related to five basic factors. These are tread wear, vehicle speed, vehicle load, tread design, and road surface. Tyre pressure is less important in its influence on the noise levels produced. In general, tyre noise is greater for lorries than for cars, and it increases with vehicle speed. Raff and Perry (1973) found tyre noise to be the predominant source of noise at motorway speed for cars. Underwood (1981) concluded that the noise produced by lorry tyres moving on a range of road surfaces (e.g. motorway surface - concrete) was affected mainly by the rolling speed of the tyre. He confirmed the other factors of importance such as tyre tread, road surface and tyre construction. Also, a Transportation Research Board (1975) study has shown that cross bar tyres are significantly noisier than rib tyres. However, studies of the noise from individual heavy vehicles show that tyre noise becomes increasingly significant at high speeds and tends to dominate at speeds above 72 km/h (Transportation Research Board, 1975).

To summarise, tyre-road noise depends on five principal factors. Their importance varies with the speed of the vehicle. There is common agreement that tyre noise is not significant in urban and suburban areas where the speed limit is below 72 km/h and traffic flow is non-steady.

2.3 TOTAL VEHICLE NOISE

The main vehicle noise sources which were discussed earlier usually combine to give the total vehicle noise levels. Variation exists in the nature of noise, which relates to the way in which each vehicle is driven. The overall vehicle noise levels have been examined in some detail by varying methods in leading countries. The well-known methods of measurement are those of the International Organisation for Standardisation, ISO, (1964), and the Society of Automotive Engineers, SAE,(American National Standards Institute, 1971). They are intended to measure the maximum A-weighted sound levels that a vehicle generates. The main difference between these methods is the microphone position for the measurement of exterior vehicle noise. The ISO test requires the microphone to be placed 7.5m from the centre line of the vehicle while SAE require 15m. The British Standards, BS 3425, (1966) is nearly identical to the ISO method.

The ISO procedure requires that the source and observer location lie on an acoustically good surface, flat and lying in an extensive open space. In a specified gear, depending on the number of gears available, the unladen vehicle approaches the observer at a specified speed and the throttle is fully opened for a distance of 10m on each side of the observer position. The ISO procedures are virtually identical with the procedures prescribed by law in EEC countries, especially for testing cars. However, manufacturers have criticised the ISO method, saying that it was not designed to reproduce the urban conditions in which it will mostly be used (OECD, 1980; Rathe, 1984). Some problems are also encountered in applying the test to heavy vehicles due to air turbulence caused by their passage.

Existing information on total vehicle noise can be classified into the following two categories:

2.3.1 Investigation of vehicle noise under steady speed conditions

Investigation of individual vehicle noise at steady speed showed that for light vehicles the level of noise increases with increasing vehicle speed (Lewis, 1973). In most cases, regression equations for the peak sound pressure level as a function of vehicle speed (V km/h) have been developed as:

$$\text{sound pressure level} = a + b \log_{10} V \qquad \ldots (2.1)$$

where a and b are empirical constants. There is some variation in the constants from one study to another, which may be explained by differences in the vehicle specifications and the operating conditions.

The noise generated by heavy vehicles has a more complicated dependence on vehicle speed. Studies of noise generated by heavy vehicles (Waters, 1974; Transportation Research Board, 1975) show that the speed dependence of the noise emissions is very similar to that for light vehicles at speeds where tyre noise dominates. In restricted situations, e.g. less than 48 km/h, the noise is less dependent because of the existence of engine noise which results from the driver's tendency to change gears very often in order to maintain optimum engine speed.

Nelson and Piner (1977) concluded that at speeds greater than 50 km/h vehicle noise increased at approximately 9 dB(A) per doubling of speed, and the total vehicle population divides most readily into light vehicles with an unladen weight not exceeding 1525 Kg and lorries. The Nelson study has also shown that variations in the noise emitted by individual vehicles within the two main groups depend as much on variations in road surface texture as on differences in vehicle weight.

It is obvious from the above review that under steady speed conditions the total noise level of vehicles increases with increasing vehicle speed. The vehicles can be classified according to their noise generation into two categories, light and heavy. This situation has been well documented.

2.3.2 Investigation of vehicle noise under non-steady speed conditions

Individual vehicle noise associated with non-steady speed conditions has received little treatment. In general, it was agreed that vehicles produce high noise levels when accelerating (Priede, 1980). It was concluded that in a maximum acceleration test the engine noise from heavy and light vehicles increased by about 8 dB(A) as compared with a constant speed test (Nilsson and Sandberg, 1982). Waters (1972) made measurements of the noise produced by two vehicles (1500 cc car and 9.5 ton lorry) under conditions of maximum acceleration. He reported that, for the lorry, the noise level generated immediately after a gear change was from 3 to 9 dB(A) higher than the equivalent constant speed value. In the case of the car, the peak level of noise is 3 dB(A) higher in bottom gear than the equivalent constant speed level.

Investigations by Harland (1974) have indicated that at lower speed drivers can choose from several possible gear ratios and the level of noise becomes much less dependent on vehicle speed. The contribution made by rolling noise to overall vehicle noise depends, among other things, on how the vehicle is being driven. It was also found at 20 km/h, for heavy vehicles, that the power system noise is 17 dB(A) noisier than rolling noise.

Nelson and Piner (1977) made a study of vehicles operating at low speeds and in non-free flow situations, and reported that six acoustically separate vehicle categories could be identified, and that these classes tended to form three rather than two distinct groups (light, medium and heavy). They also found that the noise levels from the heavy vehicles exceeded the noise levels from the light ones by about 17 dB(A), whereas under free flow conditions this difference only amounted to 9 dB(A).

Examination of vehicle noise associated with non-steady speed has produced conflicting results. This variation in the output of various studies clearly reflects the complex situations occurring in this field, such as type and age of the vehicles, methods of study, etc. So it is not easy to fix specific limits for the variation of noise levels between the different classes of vehicles. But it is becoming accepted that acceleration has more effect on overall vehicle noise level at low speeds, particularly in pulling away. The effect of pulling away varies and is greater if the cruising speed is reached quickly by maximum acceleration. The power system can cause an identical increase in total vehicle noise in built-up areas. In this case, the number of heavy vehicles plays a more significant part in increasing the level of environmental noise than in steady speed conditions.

There have been few roadside measurements taken concerned with the characteristics of total noise levels emitted when vehicles operate in realistic daily situations (see Chapter 4). These entail non-steady speeds through urban and suburban road networks, especially in the vicinity of junctions when acceleration and deceleration are very sharp. It is hoped that this research can take a step forward in this direction.

2.4 EVALUATION OF PRESENT VEHICLE NOISE CONTROL

It is twenty five years since the Wilson Committee was appointed in Great Britain to examine the nature, sources and effects of the problem of noise and to advise what further measures could be taken to mitigate it (Wilson, 1963). Since that date, vast amounts of money have been invested to control motor vehicle noise(Watkins,1981;Tyler,1985). In 1970, the British working group (Road Research Laboratory, 1970) on research into road traffic noise recommended a reduction of noise level for all cars, from 84 dB(A) to 80 dB(A) by 1975, measured in accordance with British Standards. For heavy commercial vehicles, the recommended reduction was from 89 to 86 dB(A) by the same year. The study allowed five years' research from 1970, followed by five years for design, development and production. The study also anticipated that commercial vehicle fleets would largely be replaced by quieter vehicles by about 1985.

In the United States different test methods were used (i.e SAE), and many recommendations have been issued by some states and the Environmental Protection Agency.

Figure 2.2 shows the goal of the US Department of Transportation Quiet Lorry Programme in terms of the reduction of each source and the overall sound levels. This data is for speeds less than 56 km/h and so does not include tyre noise, due to its unimportant at this speed range (Close and Wesler, 1975). The goal was based on the study of diesel lorry noise sources. It was suggested that a 10dB improvement in exhaust noise, a 5dB reduction in intake noise through the application of improved muffler and air cleaner combinations, and 7dB improvement in fan noise were possible without significantly degrading the performance or economics of the vehicle. The total noise level therefore, of 81dB(A) at 15m under maximum acceleration conditions was believed to be achievable.

The initiative for minimising individual vehicle noise can be achieved by regulations and modification of vehicles themselves or by producing a better alternative mode of transport, such as electric vehicles. These options will be examined in the following subsections.

2.4.1 Regulations

Most countries now have emission regulations for the main classes of new motor vehicles. The general features are that specific levels are set for each class of vehicle, using a test method that is usually ISO or SAE. New vehicles are subject to these standards, with occasional sample checks at intervals to ensure continuing quality. The following is a summary of leading countries' experience:

Noise level limits and their enforcement by measurement were prescribed for the first time in regulations made by the British Parliament in 1968. The maximum permitted levels were 84 dB(A) for passenger vehicles and 85 - 89 dB(A) for goods vehicles (Road Research Laboratory, 1970). The measurement is made in accordance with the test procedure described in BS 3425 in 1966. In the same year, Regulation 9, which was adopted by the Economic Commission for Europe became effective using ISO test conditions. The regulation allowed 92 dB(A) as the maximum for heavy vehicles. Further lowering of the limits came into force in connection with the European Commission Directive 77/212/EEC which was to be applicable from April 1980 for new models and would apply to existing models from 1982. The manufacturers would be required to produce vehicles with a maximum noise level of 88 dB(A) for the heaviest lorries and 80 dB(A) for cars. The council also recommended that considerable effort should be made to achieve a target of 80 dB(A) for all vehicles categories by 1985. But this recommendation was never realised. It can be seen that remarkable reductions in vehicle emission standards were proposed for cars in contrast with the British regulations, while the reduction in goods vehicle standards were to be much smaller (see Watkins (1981) for more details). At the beginning of 1984, a new EEC Directive 84/424/EEC was issued, which provides for a further lowering of the limits. The new limit value for passenger cars should be 77 dB(A) in the accelerated drive-pass test. For heavy vehicles the limits should be a maximum of 84 dB(A), depending on engine size and gross vehicle weight. These limits were intended to come into force as of 1.10.1988 for type approval and as of 1.10.89 for new registrations (EEC, 1984), but again this will not be realised.

It is clear from a review of regulation that, since 1970, European regulations have only reduced the maximum allowable noise level for goods vehicles from 92 to 88 dB(A), that is 4 dB(A) in seventeen years. However, as the regulations depend on unpredictable factors it is not anticipated that new more effective regulations will be seen for the remaining years of the 1980's.

2.4.2 Modification of the vehicles

Several countries have commenced 'quiet vehicle' programmes. The objective was to reach considerable noise level reductions in a practical manner. At the present time Britain has been carrying out a programme of development for a Quiet Heavy Vehicle for the 1990's, the QHV 90 (Tyler, 1985). The conclusions of this work contributed to the decision by the European Community to require vehicles to be quieter by the end of the decade. The British Government has stated that new lorries coming onto the road in the 1990's should be no noisier than most of the 1981 new model cars. The objective is to produce a lorry emitting 80 dB(A) under all normal operating conditions. There are also many programmes in progress as well as successful trials in other European Countries and the United States. The main purpose of these countries is also to control noise arising from future vehicular transport (Drewitz and Stigimaier, 1985).

Some of the completed projects have suggested that it is possible to reduce the exterior noise levels by 6 to 10 dB(A) for lorries. This is estimated to increase the cost of vehicles by 5 to 12%. For technical implementation, some regulations need to be changed in order to make the task of redesigning the vehicles easier. It has also been suggested that the technical means of reducing light vehicle noise by 3 - 5 dB(A) are available today. They would need 3 to 5 years' development time after being firmly decided, and could increase the cost by 3 to 10% (Rathe, 1984).

The present completed projects have shown that reduction of vehicle noise is possible in some degree, but it is obvious that all the current projects are addressed to the next decade. Also to deal with motor vehicle noise requires not only making moving vehicles quieter, but attention should be given to other types of measures which have been neglected. Such measures would be focused at the noise which vehicles make when starting, parking, accelerating and maneuvering and would include: modification of starter motor, change in the design of doors to make them less noisy when they are slammed and make horns quieter (OECD, 1980).

To date, the hope of producing quieter vehicles, which were to be in use by 1980 in accordance with the working group recommendations (Road Research Laboratory, 1970), has not yet become a reality. In addition, it is over ten years since the US Department of Transportations (Close and Wesler, 1975) issued its Quiet Lorry Programme and there is no evidence that lorries which emit a maximum 81 dB(A) level are in public use (see figure 2.2).

To conclude, it is doubtful if there will be any drastic change in the quality of the existing products of the motor industry, at least for the next fourteen years. This is due to the related unlimited variables which make such a change difficult to achieve (see section 2.5).

2.4.3 Electric vehicles

During the last few years attempts have been made to develop the electric vehicle. It was hoped that the development of such a mode of transport would have several advantages such as low noise emission and reduced cost, but the future ability of such vehicles to compete in the transport sector must now be in doubt, when set against the internal combustion engine. Aldous (1985) has confirmed that the major technological problem was and still is the battery. The quantity of batteries needed to give good performance is equivalent in weight to the payload capacity of a car or van and it takes about eight hours to charge them to give a range of 40 to 50 miles in urban driving conditions.

In terms of lack of technology, demand and investment in this field, as well as insufficient available information concerning the possible noise reduction which could be achieved as a result of its introduction, the electric vehicle is not a viable alternative to a vehicle with an internal combustion engine.

2.5 SOURCE ABATEMENT FORECAST

The previous section indicate clearly that during the last two decades remarkable efforts has been made to reduce vehicle noise. These efforts also necessitated the expenditure of vast amount of money. For example, in Britain the total cost of the recent Quiet Heavy Vehicle Programme for the 1990's is estimated to be 10 million pounds over five years (Tyler, 1985). The results of this development in vehicle noise control can be summarised in three points. Firstly, there has been a 4 dB(A) reduction of goods vehicle noise levels in accordance with European regulations, from 92 to 88 dB(A). Secondly, the hope for lorries with maximum noise level of 80 dB(A) is still the projection for the next decade. The road networks, therefore, will not effectively witness the existence of quiet vehicles in the near future. Thirdly, there is no feasible alternative to vehicles with internal combustion engines.

The main reason is that the possibility of attenuation of motor vehicle noise at source is dependent on a number of complex situations. These include:

(1) The available technology
(2) International agreement and new regulations.
(3) Vehicle markets and user demands.
(4) Problem of vehicles already in use.
(5) The accompanying increase in costs of new quiet vehicles.
(6) Competition between motor companies.
(7) Economic status of motor industry.
(8) Development in current motor vehicle plants.
(9) Time needed.
(10) Identification of the acceptable noise level.
(11) Price and availability of oil e.g. availability of cheap oil has minimised the cost of internal combustion engine vehicles.
(12) Quality of alternative road transport, i.e there is no feasible alternative mode of transport to vehicles with internal combustion engines.
(13) Difference in measurement methods for acceptable vehicle noise limits between one country and another, i.e ISO and SAE.
(14) Criticism of ISO by manufacturers.

Taking into account the slow progress in the area of control of vehicle noise at source during the years, and considering the slow replacement process of vehicles already in use and the necessity of giving vehicle manufacturers ample notice of changes in regulations, it is doubtful that any radical change will be fully perceived before the year 2000. In addition, it has also become evident that effective control of noise pollution at source is well beyond the ability of local authority engineers, because such control depends on many decisions made at national and international levels.

Moreover, an interesting comparison of overall costs for measures applied to vehicles and roads was issued by VDA (1978) in West Germany. The VDA investigation stated that the purchasers of passenger cars and commercial vehicles must spend an additional 4.16 thousand million DM each year to achieve an emission reduction on the part of the vehicles of about 5 dB(A), as compared with 1976/1977 values. In contrast, sound insulation measures, construction of new federal highways and state roads and sizeable alterations to existing ones produced costs amounting to 1.91 thousand million DM per year over a 10-year period for the whole road network. VDA, therefore, found the burden of reducing vehicle noise at source was higher for the overall economy than the additional expenditure within the municipalities, without, however, achieving a comparable control effect. So its final statement based on economic considerations emphasised on noise control measures through town planning.

Because of the advantages of such means, this study has been directed towards traffic noise abatement through design and planning (see Chapter 3).

2.6 SUMMARY

Published work shows that motor vehicles normally have a number of prominent noise sources. These are engine, intake and exhaust; cooling system; transmission; wind and tyre-road interaction. Each source's characteristics are related to the operating conditions of the vehicle in various ways. The sources are road speed or engine speed dependent.

Control of motor vehicle noise at source is always a complex target. There are a number of factors involved in arriving at acceptable levels such as the available technology; international agreement; vehicle markets; the accompanying increase in costs; time needed and difference in measurement methods. It is doubtful if there will be any drastic change in the quality of the existing products of the motor industry before the year 2000. This thesis has been directed towards the abatement of traffic noise through planning and design.

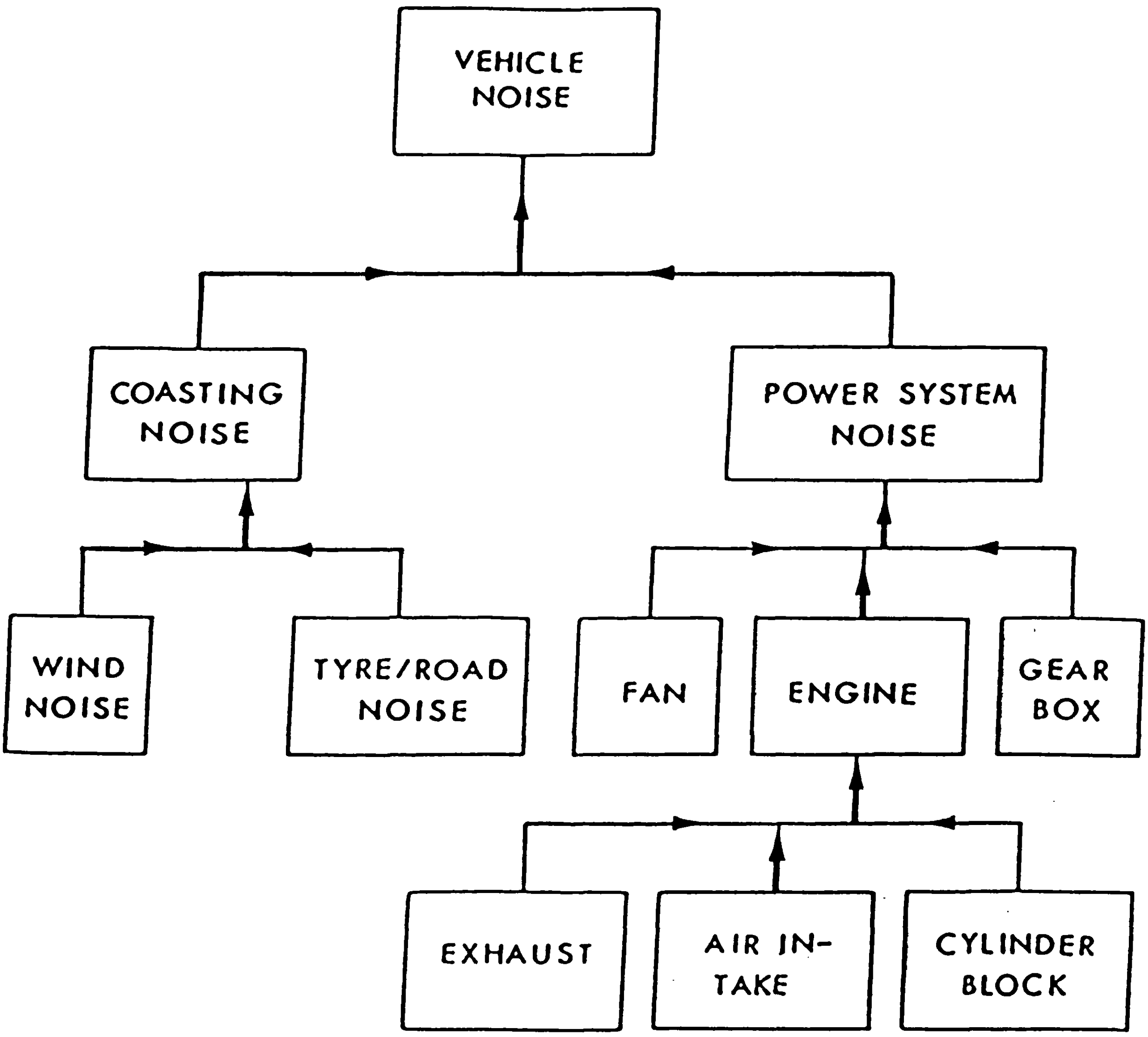


Fig. 2.1 Typical sources of motor vehicle noise

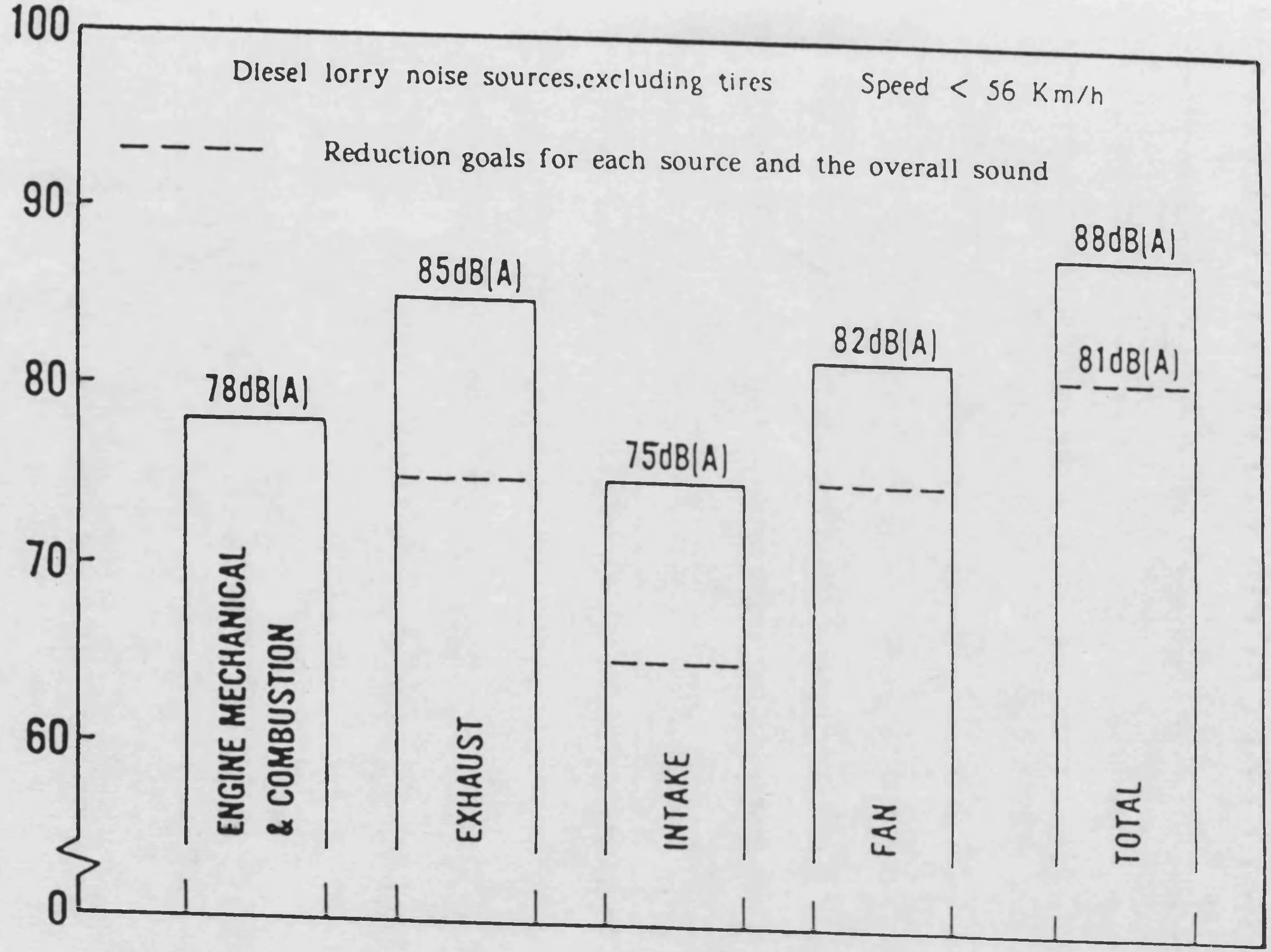


Fig 2.2 US Department of Transportation Lorry Noise Reduction Programme (Close and Wesler, 1975)

CHAPTER THREE

PRINCIPLES OF TRAFFIC NOISE CONTROL

3.1 INTRODUCTION

Noise control means achieving an acceptable noise environment at a particular reception point. In the previous chapter the first method of noise control was examined. It was seen that the wide range of problems associated with minimising the noise of vehicles at source make it unlikely that a drastic reduction can be expected in the near future. On the other hand, noise from a stream of vehicular traffic is the most convenient target for any noise control in built-up situations. This traffic noise depends upon a number of independent variables, in addition to the characteristics of the various types of motor vehicles. The variables usually affect the level of propagated noise which is heard by the recipient. The alternative method of preventing traffic noise problems is therefore concerned with the other two elements of noise abatement which are the path and the recipient, through planning and design operations.

This chapter concentrates on a review of the work that has been carried out in connection with road traffic noise control and on establishing to what degree it can help in the development of this study. The space devoted to each part of this chapter is a reflection of the extent of the relevant knowledge in these areas. The chapter is split into three main parts:

(1) Planning and traffic noise abatement
(2) Characteristics of traffic noise generation
(3) Abatement of road traffic noise

3.2 PLANNING AND TRAFFIC NOISE ABATEMENT

During the last few decades, the accelerating growth of motor vehicle use and ownership have given rise to complex problems of road traffic noise. This situation puts pressure on city engineers and planners to include noise as one of the parameters in their plans in order to be able to evaluate both existing development and future changes. In other words, they have to prevent the noise from being transmitted from a source to a receiver. Thus, the design process, coupled with the separation of noise-producing from noise-sensing subjects is an effective measure which should be employed to a greater extent for minimising the drawbacks of environmental noise. The following points illustrate the advantages of considering noise at the planning and design stages.

(1) People in their daily life are subject to traffic noise emitted by streams of mixed vehicles, rather than by specific individual vehicles. Thus, the growing awareness of the public of the adverse effects of road traffic brings about an urgent need to take account of its environmental issues at the planning and design stages.

(2) Recent governmental legislation allows compensation to be paid in terms of either a cash grant or insulation to appropriate members of the public who are exposed to noise above a certain level from road traffic. Again, this requires the consideration of traffic noise levels by city planners and engineers.

(3) Noise level limits must be determined according to the negative effects that they produce, while existing vehicle noise limits are usually subject to available technology, economics, and other factors (Previous Chapter). Also, the production of new quiet vehicles will not have a dramatic effect upon the reduction of traffic stream noise levels for some time because only a proportion of the population would purchase the new type of vehicle each year.

(4) Source reduction as an option is not one over which city engineers and planners have control. Furthermore, they cannot wait an indefinite period for the arrival of quiet transport.

(5) Traffic noise levels are influenced by those features found in built-up areas. Therefore, the appropriate method to hand is to modify the features which are responsible for the propagation of noise, and also to isolate the receiver during design and planning procedures.

3.3 CHARACTERISTICS OF TRAFFIC NOISE GENERATION

This section deals with the existing knowledge concerning the independent variables of traffic noise, in order to enable the important variables to be identified, and their likely effects on the noise from interrupted traffic flow to be assessed.

According to the available literature the factors which affect traffic noise generation are:

Road features
Traffic features
Distance from source
Building facades
Weather conditions

3.3.1 Road features

Urban road networks can be considered to fall into two areas. Those concerned with junctions, and those concerned with the stretch of road between junctions. In Britain for example, the main junction types are roundabouts, priority junctions and junctions controlled by traffic signals. The main types of urban road are (Ministry of Transport, 1966):

(1) Primary distributors, i.e all longer-distance traffic to, from, and within the town should be channelled onto the primary distributors.

(2) District distributors, i.e roads distributing traffic within the residential, industrial and principal business districts of the town.

(3) Local distributors, i.e roads distributing traffic to the areas in which considerations of the environment predominate over the use of vehicles.

(4) Access roads, i.e roads giving direct access to buildings and land within environmental areas.

Road standards have been developed scientifically for geometric and cross-sectional features of different classes of road in many developed countries (Highway Research Board, 1965; Ministry of Transport, 1966). Dynamic, physical and topographical factors have been taken into account to ensure maximum safety for road users. Traffic volume and design speed tend to be the dominant variables in determining the geometric parameters and criteria for road networks. Different design criteria have been developed in each country according to its requirements and resources, e.g. different design speed.

Urban roads should be designed to be safe and to permit the flow of traffic at reasonable speed (Jraiw, 1981). The capacity of these roads should also be balanced against the traffic requirements of both the present and proposed development of the areas they serve. There are many factors which might be expected to affect journey speed and traffic flow. Of these:

(1) Road width, distance between junctions, junction type, gradient, road surface, signs, signals and road markings.

(2) The surrounding land use, land costs and topography of the area.

(3) Working hours and well-being of commercial and industrial organisations.

(4) Change in population.

(5) Weather conditions.

In connection with environmental noise the following variables will be examined: Junctions, road width, road gradient and road surface.

3.3.1.1 Road Junctions

On an urban road system the capacity of the complete network is governed by the capacity and efficiency of the individual junctions. These are the points in the road network where the conflicts between directional demands of traffic are resolved. Thus, the various forms of traffic control at junctions are designed to allocate the available time or space within the junction to competing traffic streams (Salter, 1976).

Road junctions are usually the site of a high proportion of delays. Delays can occur in the approaches or at the junction itself. The main reasons are that vehicles have to decelerate in the approach, stop, then cross the junction itself and finally to accelerate away to cruising speed once again. Delays also occur from traffic situations within the junctions such as queuing of traffic in the approach (Maycock, 1976).

The adverse effects on people alongside urban networks range from the nuisance of stop-go motoring, congestion anxiety, pedestrian difficulties to personal accidents (Plowden, 1985). In addition, delays at road junctions constitute a massive waste of time and money. This is very important in densely populated countries such as Britain, where the time cost of delay at junctions totals several hundreds of millions of pounds per annum (Robertson, 1976).

With regard to traffic noise, very few attempts have been devoted to studying noise levels in the vicinity of different types of junctions. In general, it has been agreed that both the character and level of noise are affected by the proximity of junctions (Road Research Laboratory, 1970). Noise levels vary as vehicles slow down, stop, and accelerate. It was seen in Chapter Two that the level of noise from vehicles is often higher when starting and accelerating than when moving at a constant speed, and the former normally occurs near junctions.

At present the available information about traffic noise levels in the vicinity of various junctions is minimal. Lewis and James (1978) investigated data on light and medium traffic flows at roundabouts associated with free flowing traffic. When accelerating from roundabouts vehicles were found to generate a higher level of noise. The noise emitted by accelerating heavy vehicles was 8dB(A) higher than from light vehicles. The Lewis and James study involves freely-flowing traffic only, and they developed their study on the basis of a limited number of parameters which are insufficient to assess roundabout noise in non-free flowing situations. Also, Favre (1978) developed a computer simulation model for road traffic noise at the approach to a system of traffic lights. Consideration of L_{eq} and L_1 values illustrates that there is a traffic light influence. The main features associated with these two indices are the length of the zone of influence (about 200m), and the peak change in value up to 8-10 dB(A). The study also showed that there is a maximum increase on the accelerating side. However, model like the Favre one has not been based on a wide range of traffic data. In addition, the check on its validity concerns few field measurements. So it is not known whether such kinds of models are suitable for noise arising from non-free flowing situations. Furthermore, Favre deals only with specific conditions of non-steady flowing traffic.

It is clear from this Section that noise levels increase at junctions because of the acceleration of vehicles and the increase of noise level at low speeds, especially in pulling away. There is still an urgent need to study the influence of junctions on the environment during usual traffic operations when the road network is flanked by buildings. For the purposes of this study, therefore, it was decided to examine the influence of different junctions as they exist in everyday situations. This was for two reasons, firstly, that junctions are the most important single consideration in urban road design and planning, and secondly that they influence the environment of built-up areas.

3.3.1.2 Width of Road

Road width usually identifies the capacity of the network. It should be chosen with particular attention to the type, volume and speed of traffic which will be using the road. Thus, recommendations concerning the width for various types of roads have been issued. For example, the recommended lane width for a two-lane district distributor road is 3.60m (Ministry of Transport, 1966). It has been concluded also that the reduction in lane width from 3.65 to 2.75 decreases the capacity from 100% to 76% (Highway Research Board, 1965).

Under urban traffic conditions, narrow roads with tall buildings on either side maximise the noise level. A canyon effect is created with sound being reflected between the building facades. The Road Research Laboratory (1970) study reported that if all other factors are similar, sound level in such roads will be up to 6 dB(A) higher than in wide open roads (see also section 3.3.4).

A survey of the available research knowledge showed that road width associated with an urban environment has received little attention as a single item. Thus, an examination of the influence of road width on noise levels will be made during the course of this study, because it is important as a design parameter.

3.3.1.3 Road gradient

The field study by Kugler *etal*. (1976) has shown that the noise of heavy (diesel) lorries increases with road gradient. By comparison gradient has little influence on the noise of cars. The Kugler study also confirmed that the influence of a gradient of 2% or less is considered to be negligible for lorries, while the influence of a gradient of 7% causes an increase in the noise level of 7 dB(A).

Stephenson and Vulkan's (1968) measurements have indicated an increase in sound levels from heavy vehicles climbing steep hills. Galloway, Clark and Kerrick (1969) obtained measurements for individual cars and heavy vehicles climbing a 5 per cent gradient. No difference in the sound levels of light vehicles was observed, but, for heavy vehicles, the effect of the slope was to increase the average sound level by 2 dB(A).

Gordon, Galloway, Kugler and Nelson, (1971) reported progressive increases of 2 to 5 dB(A) from heavy vehicles, as the gradient increased from 2 to over 7 per cent for rural main roads. Scholes and Sargent (1971) predicted an increase in of 1 dB(A) for gradients ranging from 2 to 4 per cent and 2 dB(A) for those in the range 4 to 8 per cent. The British method of predicting L_{10} noise levels has also taken into account the effect of gradient. A correction has to be made for the extra noise generated by traffic at a gradient. For example, when the prevailing or existing noise is being calculated then the correction for gradient effect is given by a correction of [0.3(the percentage gradient) dB(A)], when speed is measured (Department of the Environment, 1975).

Thus, there is a general agreement that noise from heavy vehicles is increased when the vehicle is climbing a gradient. The basic reason for this is the increase in rev/min necessary to maintain speed. On the other hand, the gradient has less influence on passenger car noise. The variation in the results of surveys can be explained by the differences in the methodology used and the conditions of each study.

There have been few studies of the influence on traffic noise of road gradient under interrupted flow conditions and during routine motor vehicle activity. This is because of the gradient length and difficulties of appropriate position for surveys, which contribute to the complexity associated with investigation of road gradient noise. This study has not considered gradient due to the minimal effect of gradient on light vehicles which constitute a high proportion of traffic flow; due to the difficulty of finding a suitable location especially one where heavy vehicles exist; and due to the rarity of gradients on most of the road network in built-up situations. Therefore, only level road surfaces have been taken into account.

3.3.1.4 Road surface

There are two main types of road surface in general use on the major roads, concrete and asphalt. Raff and Perry (1973) concluded that the type of road surface in Britain is not a major variable for traffic noise consideration. From an experimental study, Franklin, Harland and Nelson (1979) concluded that, firstly, there were no significant differences in the noise emitted from vehicles running on the surfaces studied (concrete and bituminous), and secondly that the peak noise levels from light and heavy vehicles in traffic are a function of the texture depth.

In studies by Rathe (1984) on an existing asphalt road surface re-covered with a 4-centimetre thick layer of the same asphalt compound, the noise levels for regular traffic flow (10% lorries) were 2.4 to 2.5 dB(A) lower than on the untreated surface. If the thickness of the asphalt layer is increased to 10 to 15 centimetres then the expected reductions are of the order of 5-8 dB(A).

It seems from the above review that noise levels do not depend significantly on the type of surface over which the vehicles travel although the thickness of the texture plays an important part in the reduction of the noise level. Tyre-road interaction is more noticeable on motorways than in urban and suburban areas with low speed limits (see Section 2.2.6). Thus, for the purpose of this work the relation between road surface and noise level has not been studied separately. This is firstly, because this research mainly deals with areas of low speed limits where there is no obvious evidence concerning the importance of the road surface. Secondly, the selected road surfaces were roughly the same. This is true of road surface in urban and suburban areas, where the major road network surface is covered with the same material. In addition, there is the practical constraint of measuring the relative proportion of tyre-road noise in the total noise emitted from vehicles under various routine operating conditions. This is due to the unavailability of a common measurement method as well as to the difficulties of separating road surface-tyre noise from overall vehicle noise in real situations. Moreover, they are dependent on other factors. In built-up areas, in comparison with other variables contributing to the noise levels, the road surface has no clear effects. However, the developed computer model in Chapter 9 does consider this variable.

3.3.2 Traffic features

Vehicular traffic can be classed in one of two major groups: free-flowing or non free-flowing. When road traffic is freely flowing (e.g. motorways), the vehicles are travelling at roughly constant high speeds. With regard to non-free traffic operating in urban and suburban areas vehicles may be required to stop by causes outside the main traffic stream such as signs or signals at junctions.

Free-flowing traffic involves a small number of variables in cases where traffic noise is to be considered. In the case of non free-flowing traffic the situation is more complex, depending on large numbers of variables, e.g. traffic flow, speed, composition, density (e.g. continuous queue or single vehicles) and manner of driving. However, urban traffic fluctuates in terms of the above factors according to the time of the day, day of the week and month. So it is obvious that noise associated with traffic also fluctuates, and when the peak and background noise combine they produce noise levels which cause annoyance to the public. In this section the following variables will be examined as being the most important from the design point of view: traffic flow, traffic composition, and traffic speed.

3.3.2.1 Traffic flow

Traffic flow is the number of vehicles passing a specific point in a stated period of time. Flow counts usually give a direct indication of the way in which the existing road network is being used.

It has been found that noise increases with the increase of flow rate in terms of vehicles per hour. When predicting traffic noise levels by the procedure given by the Department of the Environment (1975) the basic noise level (L_{10}) is determined by the 18-hour or hourly traffic flow for a distance of 10m from the source to the receiver and the mean traffic speed of 75 km/h. It is assumed that there are no heavy vehicles in the flow and that the roadway is level. The relationships are expressed mathematically as:

$$L_{10}\,(18\text{h}) = 28.1 + 10 \log_{10} Q \text{ dB(A)} \qquad \text{... (3.1)}$$

$$L_{10}\,(\text{hourly}) = 41.2 + 10 \log_{10} Q \text{ dB(A)} \qquad \text{... (3.2)}$$

where Q is the traffic flow (v/h).

On a typical urban road, Gilbert, Moore and Simpson (1980) developed an empirical relation for noise under interrupted flow conditions:

$$L_{10} = 34.2 + 12.9 \log_{10} Q \text{ dB(A)} \qquad \dots (3.3)$$

It has been concluded that the noise level is related to the logarithm of traffic flow ($\log_{10}Q$) and an empirical formula is appropriate for the task of prediction. There has been some variation in the constant values produced by different investigations according to each investigation's resources.

The patterns of urban traffic flow are complex due to the variability of traffic flow throughout the day and because of the interaction between urban variables and the difficulty of isolating them. In the context of motorways, traffic flow varies little against time whereas in a congested urban environment it may vary considerably between one period and the next. This variation has a direct effect on the amount of traffic noise a person hears. Traffic flow,therefore, tends to be one of the most important variables in any road scheme. Incomplete knowledge also exists concerning the characteristics of traffic flow in urban areas. Thus, it was decided to examine the influence of traffic flow during this study.

3.3.2.2 Traffic composition

References have already been made to the classification of vehicles for the purposes of road design (Ministry of Transport, 1966). Classification of road vehicles for the purpose of noise prediction has also been made (Nelson and Piner, 1977). There is no doubt that since different kinds of vehicles produce different levels of noise it follows that the noise emitted by a stream of vehicles will depend upon its composition.

Near junctions, the difference in noise between cars and heavy vehicles is accentuated. Where speed increases then the difference in noise levels is less, so that on motorways the effects of traffic composition are less important than on urban roads (Road Research Laboratory, 1970).

Stephenson and Vulkan (1968) showed that there was a 6-7 dB(A) increase in mean sound level over a wide range of traffic flow at speeds ranging from 32 to 48 km/h as the percentage of commercial (heavy) vehicles increased from less than 16% to more than 50%. This is broadly consistent with the 10 dB(A) differences between cars and heavy vehicles.

In the USA, Galloway *etal*. (1969) concluded from field measurements that a large diesel truck-trailer combination would be expected to produce 10-15 dB(A) higher noise levels than a passenger car at the same road speed.

A relation was developed by Gilbert *etal*. (1980) for noise under interrupted flow conditions:

$$L_{10} = 41.9 + 11.2 \log_{10} [L + 9M + 13H] \qquad \text{... (3.4)}$$

where:

L = the number of light vehicles (v/h)

M = the number of medium vehicles (v/h)

H = the number of heavy goods vehicles (v/h)

In a non-free flow situation it has become commonly agreed that composition is speed-dependent. An increase in the proportion of heavy vehicles could decrease the mean traffic speed since heavy vehicles tend to travel slower than light vehicles. Also, the difference in noise outputs between heavy and light vehicles is greater at lower speeds than higher speeds (Bugliarello *etal*., 1976). Thus in a non-free flow situation, one can expect the percentage of heavy vehicles to be a very important factor.

The published literature suggests differences in noise levels between passenger cars and heavy vehicles which can be in the range of 2-15 dB(A). This is likely because the reliability of each traffic noise survey depends on the traffic system and other circumstances. In general, buses, coaches and heavy lorries are considerably noisier than passenger cars, and heavy vehicles affect the urban environment more than areas near motorways.

The influence of traffic composition on an urban environment, and thus its importance in any traffic management schemes and urban road design gives added incentive to include it in this study.

3.3.2.3 Traffic speed

Speed is an important parameter when studying any road scheme. It is a requirement in investigations connected with the theory of traffic flow, road design, traffic systems, signs, markings and speed limits. It is also important in relation to noise levels (Salter, 1976).

Olson (1972) found that in urban areas where traffic is free-flowing, sound levels increase between 5 and 8dB when passenger cars accelerate from the range of 30-62 km/h to the range of 96-110 km/h, while for lorries the increase is 9 dB.

A doubling of the mean traffic speed on a motorway was shown by Johnson and Saunders (1968) to give an increase of 9 dB(A).

It has been agreed that noise generated by motor vehicles, when they are driven at a steady high speed on a level road, increases with speed and takes the following form:

$$L = a + b \log_{10} V \qquad \dots (3.5)$$

where:

L = the sound level dB(A)

V = the speed (km/h)

a and b are empirical constants.

Variations in the level of increases and the constants of the above equation depend on the conditions of each survey including place and time. However, it is not clear that the effects of speed on noise generation in interrupted flow situations follow the same pattern as those of freely flowing traffic at a high and steady speed. In an urban area the speed varies from area to area and depends on the proximity of junctions, time of the day and traffic conditions and is subject to a specific limit. There appears to be very little literature available in this area that may be directly applied to the problem of traffic noise in built-up areas under interrupted flow conditions.

For the purpose of this study, it was decided to examine the influence of mean traffic speed on the level of noise for the following reasons: firstly, it is one of the dominant variables in determining the geometric parameters and criteria for road networks; secondly, current urban prediction models have not considered this variable, and thirdly, it influences the level of urban noise, because traffic speed varies from site to site in an urban area, where the noise of vehicles is significantly higher than that of traffic moving at steady speeds.

3.3.3 Distance from noise source

The level of traffic noise and its character are related to the receiver's distance from the road. Near the road, there is a substantial difference between the background and maximum noise level. But beyond a certain distance from the road, the noise from individual vehicles merges into the general traffic rumble (L_{10} and L_{90} converge). This is because an individual vehicle acts as a point source, corresponding to a reduction of 6 dB(A) for each doubling of the distance. The traffic stream as a whole may be considered as a line source, giving a reduction of 3 dB(A) per doubling of distance (Road Research Laboratory, 1970).

In general, dense traffic generates noise along the whole stretch of the road. The strength of this noise decreases as distance from the road increases, and also depends on the traffic conditions and land use.

In an urban situation where houses can be literally at the kerbside, there is little information concerning the distance probably because of the disadvantage of not having free choice to take a measurement at some distance from the road.

This study will deal with distance as a single item (simultaneous measurement - Chapter 5), and in terms of other variables because it is important when assessing the disturbance effect as well as the design of roads and buildings.

3.3.4 Location of Building facades

Non-free flowing traffic usually operates on road networks surrounded on both sides by buildings of various uses. These buildings have an influence on the level of propagated noise. Their hard, vertical surfaces reflect traffic noise back across the road. This phenomenon is termed a multiple reflection, while a road which is flanked by buildings on one side only gives rise to a single reflection. The extent to which the noise is reflected depends upon the distance of the buildings' facades from the kerbside, road width and whether or not buildings flank the road on one or two sides. Reflection also depends on the structure of the buildings and the quality of their facades.

The British method of predicting L_{10} noise levels from road traffic has been taken into account the matter of reflection effects under these conditions (Department of the Environment, 1976). To calculate noise at 1m from a facade, as required by the 1975 Regulations, a correction of +2.5 dB(A) has to be made, while the correction for a reflecting facade on the opposite side of the road is +1dB(A). However, a review of the literature shows that little work has been done concerning reflection in urban and suburban areas. Furthermore these few studies investigated the importance of the nearside building facades only (e.g. Gilbert *etal*., 1980; Fisk, Smith and Filon, 1974). This is insufficient data for worthwhile use by designers and planners because completion of their plans usually requires knowledge about nearside and farside facades - within cities most roadways are flanked to a large extent on both sides by building facades, giving rise to multiple reflection.

It was, therefore, decided to study the influence of farside and nearside building facades within the terms of this research.

3.3.5 Weather conditions

The amount of water on a road surface can serve to increase noise levels, particularly if the degree of wetness affects driving. It is possible that changes in speed and shape of the water drops in the spray thrown out behind the tyre could give rise to noise. A study by the National Swedish Board for Technical Development (Nilsson and Sandberg, 1982) indicated that a wet road surface causes up to 8 dB(A) more tyre/road noise than the same surface when dry. In the UK, Raff and Perry (1973) found that for cars and lorries on motorways the effect of a wet road is to increase the coasting noise by 10 dB(A).

Temperature was found to have no significant effect on urban noise levels (Road Research Laboratory, 1970).

To summarise, a wet road surface can influence the level of noise, while there is no clear relationship between urban noise and temperature. This study involves dry road surfaces only.

3.4 ABATEMENT OF ROAD TRAFFIC NOISE

3.4.1 Introduction

Road transport is and will remain the vital means of transportation. Every activity, such as industry, commerce, education and leisure depends on the movement of goods and people. The road transport system is thus predominant for good reasons. No other mode can compete with the flexibility and convenience of road vehicles, providing a 'door-to-door service'. Thus roads and road vehicles play a massive part in the life of the modern societies and the indication is that the amount of road traffic will increase. Gent (1984) emphasised, for example, that road transport in Britain accounts for 93% of all passenger travel and 78% of inland freight movement. Passenger travel by road is forecast to increase by 60% at the end of the century, while freight movement by road is forecast to rise by 42% in the same period.

Many factors contribute to make up a complex pattern, which must be taken into account when dealing with road transport in built-up areas. Of these:

Widespread car ownership
The rising number and enlarged capacity of goods vehicles
Public transport operations
Potential traffic
Land use
Traffic conditions
Parking management
Historic buildings and urban renewal
Development plans
Characteristics of road networks
The economic status

The connection between production and distribution centres

Congestion on roads

Vehicular delays

Pedestrian movement

Air pollution

Vibration

Traffic Noise

The central issue, therefore, is how a better balance can be struck between the use of motor vehicles and their environmental drawbacks, to maximise the benefit to society.

From the review in previous sections of various factors affecting the generation, transmission and perception of traffic noise, it is clear that noise varies a great deal according to circumstances. The noise emanating from road networks is the result of a complex situation of vehicles and the particular road configuration. The level received at any specific point of the surrounding area is equal to the total noise, of the mixture of operating vehicles, which are within hearing range. It has been seen that the magnitude of this noise level depends on the vehicle operating conditions, road and traffic features, building facades etc.

This section, therefore, turns its attention towards the practical ways of protecting the environment (the people in and around the surrounding buildings) from the unnecessary propagated traffic noise levels. It revolves around modifications of noise transmission path as well as the receiver rather than the noise source (Chapter 2), usually by employing the suitable prediction method (see Chapter 4). In other words, by the separation of noise production and noise reception. However the attenuation of traffic noise was dealt with in terms of relevance to this thesis only due to the wide scope of this topic (e.g. the design and planning processes which must include traffic noise with their traditional variables). The section can be summarised under the following topics:

Transportation planning
Road building
Traffic management
Urban planning
Building structure

3.4.2 Transportation planning

Traffic noise has not often in the past been considered as one of the parameters at the planning and design stages (see Highway Research Board, 1965; Ministry of Transport, 1966). Thus, most existing highly populated centres have developed without sufficient thought being given to the problem of noise . With the growing public awareness of environmental noise the situation has now changed, and there is an urgent requirement to keep this phenomenon at specific levels. In doing so, account must be taken not only of the traditional economic and other civil engineering factors but also of the effects of environmental noise on society.

In considering road transport systems, there are three distinct planning levels at which environmental noise evaluation needs to be considered:

(1) Long-term transportation planning: this is usually in terms of economic and engineering considerations, and based on field studies at local and national level. The development of a thorough road transport scheme normally looks ahead 15 years. At this stage, there is a need for the evaluation of a better environmental noise policy.
(2) Road network location: this stage involves a detailed evaluation of the best scheme. At the long-term planning stage it is not convenient to study

particular road locations in detail. It is often possible to decide that a specific road is essential, but there may be a number of alternative locations satisfying the main objective. So there is a requirement for a more detailed evaluation of the alternatives in order to establish the best system and this usually occurs at local level. Again the impact of road traffic noise on the environment needs to be appraised at this level. A prediction method, which is accurate, reliable and simple, is required at this stage as well as stage one.

(3) Road design: at the first two levels the scheme and its suitable position have been identified. At this third level detailed design and specification of each road section are required. So the plan must take into account all the related features, e.g. traffic directions and design speed. Environmental noise already has been considered in terms of the general factors, e.g. traffic flow, but at this stage there is a need to identify precise noise levels at each section of the network. There is a need also to estimate the number of people likely to be affected by the scheme, in connection with noise insulation regulations. This stage demands a reliable, accurate and detailed noise prediction method capable of covering all the related elements, e.g. road, traffic, building and land use classification.

It is significant to recognise between the various stages of transportation planning assessment, and to establish prediction methods suitable to each level.

3.4.3 Road building

This is also a powerful means of attaining a better environment. The benefits from a new road system usually result from the channelling of traffic that occurs when the new system opens. So traffic which formerly had no alternative but to operate through inconvenient road networks suffering delay as a result, can now operate freely. This also serves to protect the areas which used to suffer from unacceptable through traffic. Furthermore, specific schemes for junction improvements, e.g. through widening or reduction of the number of junctions, can be highly beneficial. Building and improvement of road networks provide society with many benefits such as increased efficiency of existing road transport, which affects industry, commerce and leisure etc. In terms of environmental benefits in built-up areas, new schemes can decrease the noise level, especially at the approach to junctions which are the noisiest sites in any network. Also there will be a great relief from traffic with a high proportion of heavy vehicles. New roads can also be designed specifically to decrease the noise carried to surrounding areas. The Road Research Laboratory (1970) study reported that over a complete urban area the environment can be greatly improved by concentrating traffic on to a few main routes and taking as much traffic as possible away from minor residential roads.

There are other common ways to control noise levels as follows:

(1) If a road is built below ground level, the walls of the cutting act as a barrier to the sound. The noise reduction obtained will be a function of the depth of the cutting, the angle of the wall and the cross section of the road. In urban areas this method is not easy to apply because road location depends on local topography. It may be close to many buildings, and it is always costly.

(2) For the same reason, the setting of the roads within tunnels cannot be widely used as a solution to the problem of noise in built-up areas.

(3) Acoustic barriers can be used for noise attenuation. In some cases, they provide the only means available to protect a specific area. For example, they are used in some suburban regions where motorways and relief roads are built through a residential area. Barriers usually need to be large and high enough to be effective. So this advantage makes the barriers in densely populated areas, e.g. city centres, costly and unsightly from the point of view of road users and residents or workers based in the area. Also, only limited areas can be protected by such barriers. For these

reasons acoustic barriers are not widely used in urban and suburban areas where the flow of traffic is non-free, the buildings close to the road, the land expensive and where there is pedestrian activity.

(4) Distance from the road reduces the noise level reading by the receiver. Buildings are often already close to roads and the cost of land prohibits the creation of space between new roads and buildings, so that this method is largely rejected in urban planning. However, the most convenient way of reducing noise levels in built-up areas is to consider the modification of road and traffic features through road design, using a thorough and reliable prediction methods.

3.4.4 Traffic management

Traffic management has assumed an ever increasing importance in urban areas in recent years. It is an effective tool for a better environment. A reduction in noise level can be achieved by the following course of action:

(1) The separation of networks with little traffic from those with much traffic.

(2) Limiting the access of heavy vehicles on specific road networks at specific hours or at all times.

(3) Distinguishing between through and local traffic.

(4) Restrictions that prevent drivers parking at certain areas.

(5) Pedestrian policy, e.g. Pelican Crossings.

(6) Markings and signs to inform the motorist about various actions to take.

(7) Decreasing the number of junctions and traffic lights in some suitable places. Also, switch off the traffic lights during certain periods in selected areas.

(8) Management of public transport operations.

(9) Using a computer based urban traffic control system.

Again, traffic management necessitates the existence of detailed prediction methods based on all the familiar parameters.

3.4.5 Urban planning

Urban planning is another method for the improvement of environmental conditions. This involves establishing specific zones with maximum permissible noise limits (see Section 4.5). For example, the separation of industrial and residential areas is a necessary feature in any modern city. Often the noise nuisance caused by industrial areas is due to the traffic serving the industries. It is also proposed often that new dwellings or schools should not be permitted in a noisy environment. The use of open spaces will have an effect on the overall noise climate. Tall buildings may sometimes be used to shelter the main facades of low-height buildings (Croome, 1977). However, urban planning and careful orientation of buildings is a suitable method for planners and city engineers. It is the combined responsibility of road and traffic engineers, architects, and planners to be aware of the noise control techniques relating to their activities.

Also, reduction of traffic noise through urban planning needs comprehensive and accurate prediction methods based on the features of a built-up environment.

3.4.6 Building structure

Noise in built-up areas is associated with annoyance caused in and around buildings. Thus the final component of noise control is the building's location, its actual design and insulation, rather than the transmission path and noise source.

Building noise control involves three principal issues (Croome, 1977). Firstly, the building needs to be protected from external noise sources.

Secondly it must be ensured that the building being designed is not a noise nuisance to people in the building and space nearby. Thirdly, the amount of noise generated within the building needs to be controlled.

The insulation of walls is frequently used in many countries as a means of minimising noise effects.

Windows are usually the weakest point in insulating occupants from external noise, because they attenuate the noise less than the external walls (Wilson, 1963; Croome, 1977). When windows are open the difference between noise levels outdoors and indoors is less than when the windows are closed (Scholes and Parkin, 1968). Thus, double glazing has significant effects on noise reduction.

Finally, the prevention of traffic noise becoming a problem by the appropriate use of layout and design of buildings requires comprehensive prediction methods based on the related features, while the preliminary evaluation of building location demands a simple tool.

3.5 SUMMARY

This Chapter has been concerned with a review of the work that has been carried out in many countries in connection with the control of noise levels arising as a consequence of road transport operations.

Various studies have provided evidence that the level of road transport noise is strongly dependent on related independent variables, but very little information has existed concerning the variables in built-up areas when traffic flow is non-steady.

Practical means of traffic noise abatement in built-up situations has also been reported. They were through transportation planning, road building, traffic management, urban planning and building structure. A clear need exists for a prediction tools to be employed by planners and designers to evaluate current and future development of noise levels in their area.

For the purpose of this study, the main independent variables (i.e junctions; road width and surface; traffic flow, composition and speed; distance from source, distance of building facades; and weather conditions) were identified.

CHAPTER FOUR

THE PRESENT STATE OF PREDICTION METHODS FOR ROAD TRAFFIC NOISE

4.1 INTRODUCTION

The previous chapter has identified the features on which generation of traffic noise depends, and the practical methods of abatement. This chapter deals with the manner by which the relationship between the emitted noise and these features may be examined.

From international experience it has been found convenient to establish the relationship between noise level and related features by formulating means of prediction. Thus, various types of prediction models have been utilised until now.

While there is slow progress in minimising vehicle noise at source, it is obvious that traffic noise surveys are time consuming and require skilled staff and expensive equipment. Consequently, prediction methods can help by providing a tool for assessing the various consequences of the scheme under consideration. Prediction methods can help to find the best ways of using road networks, by balancing the travel needs of vehicle users and pedestrians on the one hand and the environmental cost of travel on the other. The decision-maker can then develop schemes which meet the needs of the community, but the method chosen must be shown to be suitable and accurate.

Over the past twenty years most of the prediction methods have been related to noise from high speed freely flowing traffic on road networks which were unflanked by buildings. With regard to noise from non-free flowing traffic in built-up areas the situation is more complex. Yet this complex situation has not been modelled properly.

The chapter is split into six main parts. Again, the space given to each part of this chapter reflects the degree of relevance of the existing practice to this study.

(1) Structure of traffic noise in built-up areas
(2) Traffic noise indices
(3) Measurement of traffic noise
(4) The recommended noise levels
(5) Current prediction methods of road traffic noise
(6) The need for further investigation

4.2 STRUCTURE OF TRAFFIC NOISE IN BUILT-UP AREAS

The noise level emanating from road networks is the result of the complex interaction of individual vehicles which has previously been discussed, and the particular road layout. Identification of emanating noise from road traffic may be classified according to four possible situations as follows:

(1) and (2) concern free flowing traffic which usually relates to a condition where vehicles traversing a section of a roadway are not required to stop by any cause external to the traffic stream such as signalised intersections, e.g. a motorway

(1) Freely flowing traffic - Free noise propagation

Free noise propagation occurs when a road network is surrounded by open areas.

(2) Freely flowing traffic - Restricted noise propagation

Restricted noise propagation usually occurs when a road is surrounded by buildings or barriers.

(3) and (4) deal with non-free flowing traffic which is a condition where vehicles traverse a section of a roadway are required to stop by a cause outside the main traffic stream such as signs at junctions, e.g. urban areas.

(3) Non-free flowing traffic - Free noise propagation

(4) Non-free flowing traffic - Restricted noise propagation

Traffic noise in built-up areas (point 4 above) is different from that produced by, say, traffic on motorways. This noise is generated in areas of different road configurations surrounded by buildings of used in various ways with a high density of inhabitants, while, for example, motorway noise affects only particular land use and is subject to specific variables. Usually the vehicles in built-up areas follow specific driving needs such as decelerating, stopping and accelerating, which are predominant at junctions and constitute fundamental factors in any environmental issue.

It is generally agreed that in built-up areas traffic produces noise levels that fluctuate with time, and that these vary according to vehicle maneuvers, which increase the level of traffic noise significantly. Heavy lorries in the volume of traffic have a great effect on noise level. As the buildings are sufficiently close to the side of the roads, the noise can be reflected back into the source and vice versa. Stop-start traffic causes a massive waste of time and is ugly (Waters, 1974; Maycock, 1976; Alexandre *etal*., 1975).

However, the characteristics of traffic noise from freely flowing traffic have been thoroughly assessed and modelled. There is incomplete knowledge concerning the fourth situation on which this study is based.

4.3 TRAFFIC NOISE INDICES

In the development of an index for the measurement and quantification of noise, several goals have been defined (Scholes, 1970):

(1) The unit should have reasonable predictive accuracy.
(2) The application of the unit should limit noise levels so that conditions will be acceptable to a known proportion of the population.
(3) The noise reduction measures needed to achieve the acceptable level will not be unduly expensive.
(4) The units should be capable of being calculated from details of traffic flow, propagation paths and insulation measures.

The results of social surveys carried out to assess the annoyance caused to people by traffic noise have led to the establishment of many noise indices. These indices have been devised to take account of the disturbing qualities of noise and to correlate with subjective response. They are therefore useful for planning purposes, especially when a reliable prediction model is possible. Up to the present time there have been quite a large number of noise indices proposed for the calculation of road traffic noise. Fortunately many have fallen from common application. Table 4.1 illustrates indices used in several countries. The following investigation will briefly review those indices which have received most attention, such as:

The percentile level
The equivalent sound level
The traffic noise index
The noise pollution level
The day-night average sound level

4.3.1 The percentile level

One of the most common methods of measuring traffic noise is to use percentile levels. These are written Lx and represent the level of noise which is exceeded for x% of a specific time.

Road traffic produces noise levels that fluctuate with time. This fluctuating noise varies greatly according to road and traffic features. For example, the highest peaks are caused by heavy lorries and the width of the peaks and their frequency depends on traffic composition and speed of the traffic. Usually, such noise levels are statistically analysed to determine the frequency of occurrence of each noise level or band of noise level. When statistical data is plotted in the form of cumulative distribution it is quite straightforward to determine the noise levels that are exceeded for a certain percentage of the time. Most commonly L_{10}, L_{50} and L_{90}, the A-weighted noise levels exceeded 10% , 50% and 90% of the time, are calculated.

The L_{10} represents a well known way of expressing exposure to noise over a period of time. After the Wilson Committee in Britain made a number of recommendations, it came into wide use (Wilson, 1963). The index is also recommended for use by the Noise Advisory Council (1975). It forms the basis of the noise insulation regulations, 1975, which provide compensation for excessive noise from new roads (House of Commons, 1975). Official design rules are also available for prediction of L_{10} (Department of the Environment, 1975). At free flow sites the average L_{10} both over 12 and 24 hours has been found to correlate well with dissatisfaction, and L_{50} and L_{90} levels treated in the same manner produced only a slightly reduced correlation (Langdon and Buller, 1977).

As well as for motorways, L_{10} dB(A), is used in prediction of noise from freely flowing traffic under rural and urban conditions (Nelson and Godfrey, 1974; Burgess, 1977). In the USA, Canada and Australia, L_{10} dB(A) has also been used to measure highway noise (see Table 4.1).

The level exceeded for ninety percent of the time, L_{90}, is effectively the background level, whereas L_{10} distinguishes the higher levels of noise. The sound level that is exceeded 50 percent of the time, L_{50}, is also used as a criterion in some countries (see Table 4.1).

For the purpose of this study, L_{10} dB(A) was one of the indices chosen for the following reasons:

(1) Previous studies showed its suitability for measurement of noise levels occurring in traffic systems in Britain, where this research has been carried out.
(2) Previous experience showed it to correlate well with the public's response.
(3) Most attempts to evaluate urban traffic noise are based on L_{10} dB(A).
(4) In order to develop meaningful methods, it is important to have continuity with previous practice, Section 4.6.

In addition to the above advantages, the reliability of L_{10} was examined during the experimental procedures of this study and found to be satisfactory. L_{50} and L_{90} were also evaluated (Chapters 5-9).

4.3.2 The equivalent sound level (L_{eq})

The equivalent sound level represents another index for describing noise. This index defines the total noise exposure rather than a noise which is present for a given percentage of the time. For example, suppose sound pressure varies during the period of an hour, being 80 dB(A) during the first half hour and 70 dB(A) during the second half. The L_{eq} during this period is 77.4 dB(A) . To arrive at this conclusion, the following expression is applied:

$$L_{eq} = 10 \log_{10}[\frac{1}{100}\Sigma f_i \, 10^{\frac{L_i}{10}}] \qquad \text{... (4.1)}$$

Where:

L_i = the median sound level of the i th 5 dB(A) interval

f_i = Percentage of the total time that a sound level is in the i th interval.

A Swiss study (Croome, 1977; Nemecek, Wehrli and Turrian, 1981) produces the following formula for traffic noise levels:

$$L_{eq} = L_{50} + 0.43(L_1 - L_{50}) \qquad \text{... (4.2)}$$

In the UK, Robinson (1969) has adopted a different relationship for noise from freely flowing traffic:

$$L_{eq} = L_{50} + \frac{(L_{10}-L_{90})^2}{65} \qquad \text{... (4.3)}$$

The L_{eq} is used widely in Western Europe as a traffic noise unit (see Table 4.1). With regard to L_{10} the following relationship was expressed (Driscoll, Webster, Haag and Farinacci, 1974):

$$L_{eq} = L_{10} - 3 \qquad \text{... (4.4)}$$

L_{eq} will also be applied during the course of this research for the following reasons:

(1) The Noise Advisory Council (1978), has recommended a gradual transition to the use of L_{eq} in Britain, for quantification of the noise environment from each source and from all sources together, in order to

avoid the confusion which resulted from different modes of evaluation and to make comparison easier.

(2) It is widely used in some European countries and it has recently come into favour in the United States (Louden, 1985).

(3) This index has been found to correlate well with dissatisfaction, under freely flowing traffic when averaged out over 24 hours (Langdon and Buller, 1977).

(4) Attempts to develop a prediction method for noise from non-free flowing traffic have been accompanied by incomplete knowledge about L_{eq} performance, Section 4.6. Meanwhile, its increasing importance demands that it should be evaluated in greater detail.

The validity of L_{eq} as a noise index has also been examined during the development of this study and showed satisfactory results (Chapters 5-9).

4.3.3 Traffic Noise Index (TNI)

The Traffic Noise Index was the result of a traffic noise survey at fourteen sites in London, organised by the Building Research Station (Griffiths and Langdon, 1968). Various indices were tested, but a combination of indices which was named the TNI was found to give the best correlation, to a degree of 0.81, with median dissatisfaction scores for the sites. The technique is defined as:

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \quad \text{... (4.5)}$$

Where 30 is a constant. This index has not been regarded as a suitable standard for traffic noise in Britain by The Noise Advisory Council (1975). The index also has not proved its reliability during the course of this study (Chapter 6). Thus it has not been discussed in detail in this thesis.

4.3.4 Noise pollution level (L_{np})

Robinson (1969) proposes the noise pollution level as the basis of a unified system. It is based on two terms, one representing the equivalent continuous noise level dB(A) and the other representing the annoyance due to fluctuations in the noise level. L_{np} is defined as follows:

$$L_{np} = L_{eq} + 2.56\,\sigma \qquad \text{... (4.6)}$$

Where σ is a standard deviation of the instantaneous level in dB(A).

The L_{np} index has fallen from worldwide application and has shown no reliability during the process of this study (Chapter 6). It has therefore been disregarded.

4.3.5 Day-Night average sound level (L_{dn})

L_{dn} is an alternative index for road traffic noise that has been formulated in the USA. It is defined as the L_{eq} A-weighted sound level during a 24 hour period with a 10 dB penalty for night time sound levels. By 'day-time' is meant the time between 07.00 and 22.00 hours while 'night - time' is between 22.00 and 07.00 hours. The US Environmental Protection Agency has adopted the L_{dn} as the rating method to describe long-term annoyance from environmental noise (Schultz, 1982). It is not clear whether the L_{dn} is suitable for use in the UK. L_{dn} will not be examined during the process of this study because of its unpopularity.

Country	Noise Description	Application
GB	L_{10} L_{eq}	Traffic Noise General Environmental
USA	L_{10} L_{dn}/L_{eq}	Highway Noise General Environmental and highway noise
W Germany	L_{eq}	Traffic Noise
Italy	L_{eq}	Traffic Noise
France	L_{50} L_{eq}	Express-way Rail and Urban Traffic Noise
Sweden	L_{eq}	Traffic Noise
Switzerland	L_1/L_{50} L_{eq}	Traffic Noise
Japan	L_{50}	Traffic Noise
Canada	L_{10} L_{eq}	Highway Noise Road and Rail Noise
Australia	L_{10}	Traffic Noise

Table 4.1 Environmental Noise Indices used in several Countries (Dept. of the Env., 1975; The Noise Advisory Council, 1978; Croome, 1977; Schultz, 1982; Nilsson and Sandberg, 1982; Hajek, 1975; CMHC, 1981; Igarashi, 1984).

4.4 MEASUREMENT OF TRAFFIC NOISE

4.4.1 Types of traffic noise survey

The measurement of traffic noise usually deals with two areas. Firstly, individual vehicles are tested to establish whether the noise generated by them is below the legal limit (Chapter 2). Secondly, measurements of noise emanating from a stream of road vehicles are taken, in order to obtain data which can be used for planning purposes. As mentioned earlier (Chapter 3), measurement of noise from the second point of view is more significant to the public and it is the area with which this study is involved.

During the last twenty five years a remarkable number of traffic noise surveys have been made around the world. Each survey has provided a picture of a specific situation; dependent on each study's objective methods, indíces, place and time. For example, in a London survey, it was found that the L_{10} value reached 82 dB(A), when the measurements were made very close to the road (Parkin, Purkis, Stephenson and Schlaffenberg, 1968). Measurements in Massachusetts found that the L_{10} level of 62.5 dB(A) occurred during morning rush hours (Wesler, 1973). Cannelli (1974) found traffic noise levels in central Rome much higher than in London or Paris. L_{10} values from 67 to 93 dB(A) were reported with the L_{50} values from 61 to 90 dB(A).

In addition, several noise surveys have dealt with the simultaneous measurement of specific parameters together with noise, and these have been used to establish prediction formulas (Section 4.6). Other surveys have been extended to the public's reaction to its surrounding environment by means of a social survey (see Chapter 8).

This thesis involves the examination of traffic noise levels and the parameters relating to them, as well as the public's reaction.

4.4.2 Sampling of noise level

Measurement of traffic noise is often achieved by the collection of one sample each hour, to avoid continuous measurements. The sample is less than 60 minutes while the continuous measurements are over a 24 hour period. Thus, many attempts have been made to assess the error margin between sampled and continuous investigations. Safeer (1972) indicated that at positions where the noise sources are homogeneous, a small number of short samples may be adequate to represent the actual noise conditions. Where the sound levels are from a variety of different sources which randomly appear, more extensive sampling may be necessary. A Department of the Environment (1975) design guide recommended that the sample length should not be less than 5 minutes, or greater than 55 minutes in each hour. There is disagreement in the available information concerning the error limits produced by various sampling schemes. But it has become the general practice to use the sample method, as the continuous requires extra time and money. As far as urban traffic noise is considered, it is beyond doubt that the longer the sample is, the more accurate conclusion will be obtained because such noise varies sharply during the day and night according to traffic operations. This research, therefore, has been concentrated upon thirty-minute samples (see Section 5.6).

4.4.3 Measurement system

The type of noise and the required measurement accuracy dictate the particular equipment chosen to monitor and measure noise. Furthermore, the equipment should meet the specifications issued by national and international organisations. Thus, noise measurement should produce accurate and thorough information which clearly illustrates the acoustic situation of interest. Objective measuring instruments, therefore, have been modified by various researchers to provide an acceptable correlation with human response and to establish useful units in a planning and design context.

The basic instrument for the objective measurement of noise is known as the sound level meter, while the unit for measuring is the 'decibel (dB) scale'.

In an attempt to correlate subjective judgements of noise with the objective readings obtained from measuring instruments, sound level meters are fitted with four internationally defined weighting filters A,B,C and D. In practice it has been found that for motor vehicle noise the 'A' weighted decibel (dB(A)) is the simplest and most convenient indicator of subjective responses (Wilson, 1963). The B, C and D weighting networks are relatively infrequently employed. The B is intended for sounds of medium intensity, C is intended for loud sounds and D for the measurement of jet aircraft noise. Unweighted sound levels are also measured in connection with frequency analyses, e.g. the Frequency Spectrum (Hassall and Zaveri, 1979).

There are several types of system in use for statistical sampling of noise levels (Bruel and Kjaer, 1975, The Noise Advisory Council, 1978). The best-known system for traffic noise measurement and analysis is one which employs the following typical equipment with a sound level meter.

(1) Sound level calibrator: This is a small pocket unit, which provides quick and accurate direct calibration of sound measuring equipment.
(2) Windshield: Field measurements should include a windshield placed over the microphone of the sound level meter.
(3) Tape recorder: This is used to provide permanent storage of measured sound.
(4) Audio Frequency Spectrometer: This is primarily designed for analysing the field data. It consists of an output and input amplifier, a band-pass filter, and weighting networks.

(5) Level recorder: This is used to provide a permanent graphic recording of measured sound level fluctuations over a period of time.

(6) Statistical analyser: This equipment automatically samples the sound level at fixed intervals of time.

To determine the road traffic noise level objectively at a particular location, a knowledge is required of the mean values of noise indices, e.g. L_{10}, over a specific period such as 18 hours (Department of the Environment, 1975). The main point of interest here is the position of the sound level meter. To measure noise from traffic travelling at high speed, previous studies have been made at considerable distances from the road, for example 120m (Delany, Harland, Hood and Scholes, 1976). In built-up situations where the buildings closely surround the road network on both sides and the flow of traffic is non-steady and subject to a 48 km/h limit, little field information is available. However, the available literature indicates that the measurements have been made close to the road. For example, Oakes and Tomlinson (1973) who dealt with traffic noise problems in urban areas, recommended the convenience of measurement at the kerbside to avoid pedestrian interference. This recommendation was based on field investigations. Mention should also be made of well-known field surveys carried out in this context in Britain. These surveys were also conducted at 1m from the nearside kerb in congested areas. Prediction models were obtained for noise level (L_{10}) from urban traffic under interrupted flow conditions (Gilbert *etal*., 1980), see Section 4.6.

For the purpose of this study, most of the measurements have been made at 1m from the nearside kerb and the above set of equipment was used. To deal with the variety of situations, measurements were also made at 1m from the nearside facade or at various distances between the nearside kerb and nearside facade (next Chapters).

4.5 THE RECOMMENDED NOISE LEVELS

Of great importance in the design stage is the consideration of the population affected by noise, that is, the receivers and the path of propagation to them. Having identified the people affected by the noise source, it is then necessary to examine the acceptable noise limitations to be accepted by those individuals.

The recommended individual vehicle noise limits discussed earlier (Chapter 2) are not necessarily based on people's response to their surrounding environment. Thus, other recommendations for noise levels in outdoor and indoor environments have been set after consideration, by a combination of physical and social surveys, of the noise to which people are exposed and their subjective response to it. For instance, the Swedish traffic noise commission recommended in 1974, that in newly built-up areas, the aim should be to reduce the general traffic noise outdoors to L_{eq} = 55 dB(A) and indoors to L_{eq} = 30 (Nilsson and Sandberg, 1982). In France, the recommended daytime noise standard is that the average noise level, L_{50}, should not exceed the 45 dB(A) level inside a building in residential areas. The corresponding facade level is 60 dB(A). It was recommended that in areas with L_{50} of over 70 dB(A) housing construction should not be permitted (Watkins, 1981). In Japan, a daytime L_{50} level of 50 dB(A) is specified for zones used for dwellings only. The equivalent night level is 40 dB(A). A maximum daytime L_{50} level of 60-65 dB(A) is specified for areas surrounding wider roads or used for commercial and industrial purposes (Watkins, 1981). The US noise level standards were issued by the Federal Highway Administration in 1972 as a Policy which adopted the L_{10} dB(A) as the main statistical indicator for evaluating highway traffic noise. The outdoor L_{10} dB(A) level should not exceed 70 dB(A) in residential areas, while the suggested indoor level was 55 dB(A) (Federal Highway Administration, 1972). In addition, the US Environmental Protection Agency recommends an L_{dn} of 55 dB(A) as a desirable outdoor noise level for residential neighbourhoods, while the suggested indoor level was 45 (Schultz, 1982). In West Germany a design guide level was introduced for which values are given in the form of L_{eq} dB(A). The L_{eq} (day) should not exceed 55 dB(A) in residential areas and L_{eq} (night) should not exceed 45. For special areas only (depending on the type of land use and percentage of housing) 70 dB(A) is permitted (VDA, 1978). In Switzerland, the recommended external sound levels in front of the windows of dwellings should not exceed the level of L_{eq} (day) = 60 dB(A) and L_{eq} (night) = 50 for a residential area (Croome, 1977). The recommended level of external noise in Britain for outside a residence is L_{10} dB(A) = 68 (House of Commons, 1975).

It appears that the recommended L_{10} level outside a building in living areas ranges between 68-70 dB(A), while for countries who follow L_{eq} the outdoor level ranges between 45 and 60 dB(A). The recommended daytime level for L_{50} countries is between 50 and 60 dB(A). An L_{dn} of 55 dB(A) was suggested as a desirable outside level.

It is hoped that this section represents some of the ideas about the acceptable degree of traffic noise levels reported by previous researchers.

4.6 CURRENT PREDICTION METHODS OF ROAD TRAFFIC NOISE

The purpose of planning is to regulate and encourage changes in such a way as to maximise the benefits to society. In order to do this it is necessary to be able to predict the effects which existing and new schemes will have on people and to evaluate these effects on the surrounding community and the environment.

The availability of prediction method has several advantages as follows:

(1) It saves time and money.

(2) It avoids unusual weather conditions which affect the accuracy of measurements.

(3) It is not always easy to find measurement locations associated with specific conditions at a convenient time or place.

(4) Prediction methods give the decision-makers freedom to modify any variable in order to create the best system.

(5) Prediction methods make it possible to avoid the influence of factors such as unusual traffic congestion, due to maintenance or accidents, which may otherwise affect the accuracy of field measurements.

(6) It is convenient to have a prediction tool which relies on existing transportation engineering methods.

The problem of modelling traffic noise has been approached from two main directions. Firstly, given traffic and road features, forecasting models have defined noise from high speed, freely flowing traffic on road networks which were not flanked by buildings. Such models usually involve a steady noise level, a small number of parameters and have been well documented. The second concern is the modelling of noise from non-free flowing traffic in built-up areas (Section 4.2). This development is more complex. In this case, normally the buildings are sufficiently close to the roads and hence cause noise reflection (Section 3.3.4). Noise also depends on the specific driving needs of vehicles as well as traffic lights and signs which are to control traffic flow and speed (Section 3.3.1.1). Furthermore non-free flowing models have to deal with low speeds, changeable noise levels and interaction between large numbers of related variables which make their separation difficult. As yet noise from non-free flowing situations has not been modelled properly.

Leaving aside the limitations of non-free flowing traffic models, most of the prediction techniques in current use for free and non-free flowing traffic fall into two categories depending upon whether they calculate L_{10} or L_{eq} dB(A), (Section 4.3). In general, the complexity of modelling the factors affecting the character and level of noise is reflected in the discrepancies between measured and predicted noise levels. Differences in findings are obtained when using the various methods depending upon, for example, the number of parameters included and their design importance, and the conditions of model construction. Therefore, once the models have been based on most of the common elements & conditions and found to give acceptable differences between predicted and actual data, they can be accepted and employed for traffic noise forecasting.

The aim of this section is to assess the existing knowledge pertinent to the evolution of prediction models and to determine which of them might be suitable for this study. The review will give more weight to the United Kingdom's experience since the UK is a leading country in this field and because this research has been carried out in Britain. The interaction between noise level (dependent parameter) and the independent parameters has been examined in three main ways which may be classified under the following headings :

Regression analysis models
Theoretical models
Scale models

4.6.1 Regression analysis models

The mathematical model is already more common than may be realised. Such models employ symbols to represent the variables or elements of the system. They serve to simulate the behavioural characteristics of the case being analysed. In order to formulate a prediction model for traffic noise, one of the principal methods is the establishment of empirical models, using multiple regression analysis. In fact the use of this tool seems to have arisen as early as the measurements themselves. It has also been common in transportation engineering for many decades. In addition, the rapid improvement of the electronic digital computer has been responsible for the wide employment of regression analysis. Therefore, most prediction techniques in current use around the world are based on the regression method. The main advantage of this concept is its employment in conditions where little is known about the interaction between the variables, by correlating the dependent variable with certain functions of the independent variables. This kind of model is usually based on field measurements and represents the case as it exists in real daily life (see Delany, 1972a). It is essential to any traffic noise study. Also, even most of the theoretical models or computer simulation models based on field studies employ the regression method to identify the significant parameters (Jones and Hothersall, 1980).

Evidence from several sources, especially for free flowing traffic, has shown that the level of noise is related to the logarithm of traffic flow ($\log_{10} Q$) and speed ($\log_{10} V$) and related linearly to the proportion of heavy vehicles (Delany, 1972a). This has led to the derivation of regression equations having the following form:

$$L = a_0 + a_1 \log_{10}V + a_2 \log_{10}Q + a_3P \qquad \text{... (4.7)}$$

L = mean noise level dB(A)

V = mean traffic speed (km/h)

Q = mean traffic flow (v/h)

P = percentage of heavy vehicles (%)

a_0, a_1, a_2 & a_3 are regression coefficients, dependent on the methodology and circumstances of each survey.

4.6.1.1 Regression models for free flowing traffic

In the light of the official recommendation of the Wilson Committee

(Wilson, 1963), one of the earliest trials for the prediction of traffic noise was the Greater London Council (1970) Design Bulletin. The main disadvantage of the method was that it did not take into account the variation of noise level with traffic parameters, e.g. it recommended kerbside values of 83 dB(A) (Delany, 1972b). This was followed by the Building Research Station Digest 135 which embodied published work by Scholes and Sargent (1971). The basic prediction was by means of a graph relating 18hr L_{10} (at 30m from the nearside edge of the carriageway) to the number of vehicles per 18 hour day. This level was for a point 1m from the house facade, with a 75km/hr mean traffic speed and 20% heavy vehicles. The graph was obtained from the equation:

$$L_{10} = 7.5 \log_{10}(\text{flow per 18 hours}) + 41.5 \qquad \text{... (4.8)}$$

Again, Building Research Station methods showed the limitations of their prediction data (see Delany, 1972b).

At the National Physical Laboratory, development has also been carried out. Many aspects of road traffic noise have been investigated by Delany (1972a) and the following formula was evolved at the reference distance of 7.5m from the traffic stream, based on regression analysis:

$$L_{10} = 17.56 + 16.36 \log_{10} V + 8.97 \log_{10} Q + 0.117 P \qquad \text{... (4.9)}$$

The result shows that L_{10} increases by 4.9 dB(A) per doubling of speed and by 2.7 dB(A) per doubling of flow. Equations in terms of L_{50} and L_{90} were also developed. Delany followed this report by another prediction method for calculating L_{10} from freely flowing traffic out to a reference distance of 120m from the centre of traffic flow, based on the same variables.

While the above studies used single regression coefficients, Nelson (1973), at the Transport and Road Research Laboratory, found some interdependence, particularly with the percentage of heavy vehicles. The L_{10} index is given by the equation:

$$L_{10} = 27.4 + 0.3\,P + (20.4 - 0.18\,P)\log_{10}V + (8.0 + 0.05\,P)\log_{10}Q - 16\log_{10}d \qquad \text{... (4.10)}$$

where:

d= distance from the nearside kerb (m).

The effect of mean traffic speed on L_{10} reduces as the proportion of heavy vehicles increases. In the absence of any heavy vehicles L_{10} increases by 6.1 dB(A) per doubling of speed whereas the corresponding increase is about 4 dB(A) for a composition containing 40% heavy vehicles. The increase in L_{10} per doubling of traffic flow varies between 2.4 and 3 dB(A) as the percentage of heavy vehicles varies from 0 to 40%. The Nelson model is also only suitable for freely flowing traffic.

In view of the need for the official standards which were stipulated in the 1975 revision of the noise insulation regulations (House of Commons, 1975), and to overcome the problem of a number of conflicting prediction models from various sources, the official Design Guide in Britain was issued by the Department of the Environment (1975). In order to predict traffic noise, the Guide deals with the assessment of the basic noise levels in terms of hourly or 18h L_{10} dB(A). Two design charts are presented, one gives the basic noise level as L_{10} 18h in terms of total 18h flow rate and the other the hourly L_{10} in terms of total hourly flow rate. In both design charts the mean speed of the traffic stream is 75 km/h, the proportion of heavy vehicles is zero and the road is assumed to be level. The mathematical relationships are shown in equations 4.11. A correction must then be made for the speed of the traffic where it differs from 75 km/h and for the percentage of heavy vehicles in the flow. A further correction to the basic noise level must also be made for the gradient, road surface, distance, nature of ground between traffic noise source and the reception point, barrier and angle of view.

The Department of the Environment (DOE) method resulted in the following prediction model at the reference distance of 10m (see also Delany *etal*., 1976):

$$L_{10} = 10 \log_{10} Q + 33 \log_{10} (V + 40 + 500/V) + 10 \log_{10} (1 + 5P/V) - 27.6 \qquad \text{... (4.11)}$$

The above formula deals with V under two circumstances. Noise level decreases as speed (V) increases in the element 33 $\log_{10}$ (V + 40 + 500/V). In the element 10 $\log_{10}$ (1 + 5P/V) speed also involves an interaction with P. The technique entails that for any given P the estimated L_{10} decreases as V increases.

The DOE method is claimed to be valid for both free and non-free flowing traffic. But it does not explicitly consider in the formulation the vehicle flows in low rate, low speed and stop-start traffic situations associated with built-up areas. Furthermore, by applying the data from an interrupted traffic flow, a larger margin of error was found by Gilbert *etal*. (1980) and this study (Chapter 7).

Using Regression Analysis methods, prediction models have also been developed in many other countries, notably, the Ontario method. This is a regression model in the form of nomographs, based on 133 noise measurements taken at 120 locations near rural and urban freeways, highways and residential streets (Hajek, 1975). The mathematical form is:

$$L_{10} = 52.7 + 11.2 \log_{10} (Vc+3Vt) - 14.8 \log_{10} d + 0.21\, S \qquad \text{... (4.12)}$$

where:

V_c = hourly car volume (v/h)

V_t = hourly lorry volume (v/h)

d = the distance of the observer from the edge of the pavement (m)

S = average vehicular speed (km/h)

The standard error of L_{10} levels calculated by the Ontario method was about 2.2 dB(A). The model was valid for free flowing situations. No facades or non-free flowing cases were studied.

Based on L_{eq} dB(A), a similar Ontario method was developed (Jones and Vermeulen, 1978):

$$L_{eq} = 49.5 + 10.2 \log_{10}(V_c + 6V_t) - 13.9 \log_{10}D + 0.21S \qquad \text{... (4.13)}$$

Also, L_{eq} in terms of regression methods is employed in West Germany (Louden, 1985)

$$L_{eq} = 36.8 + 10 \log_{10}(M(1+0.082P)) + K \qquad \text{... (4.14)}$$

where:

M = Total vehicle flow per hour

P = Percentage of heavy vehicles

K = Correcting term for the maximum allowable speed

Regression models for traffic noise in built-up areas under freely flowing traffic have been established by Burgess (1976). They estimated noise levels in terms of L_{eq} and L_{10} dB(A). But they are based on the same free flowing variables and they do not take into consideration most of the parameters of built-up areas.

Their final forms are:-

$$L_{10} = 56.0 + 10.7 \log_{10}Q + 0.3P - 18.5 \log_{10}d \qquad \text{... (4.15)}$$

$$L_{eq} = 55.0 + 10.2 \log_{10}Q + 0.3P - 19.3 \log_{10}d \qquad \text{... (4.16)}$$

where:

d = distance from centre of flow of nearside carriageway (m)

To summarise, it is clear that the prediction models for noise arising from freely flowing traffic are well established. The main discrepancy between the methods is the variation in correlation coefficients which affects the validity of relationships between the parameters and the noise levels. The conflict is expected because of the difference in the conditions of each survey such as time, place, study objective, traffic status, road layouts and driving manner.

The main philosophy of all prediction models for free-flowing traffic is found to be similar despite the differences between the form of methods employed by each country. They all used specific variables such as traffic speed, flow, percentage of heavy vehicles, and distance between the survey point and the traffic. They concluded that noise levels increase with increase of speed, flow and composition, while they decrease with increase of distance.

4.6.1.2 Regression models for non-free flowing traffic

To predict noise from traffic in non-free flowing situations it appears that regression models are the only convenient approach. For the modelling of this situation more information is needed and more parameters have to be included in the analysis. Attempts have been made in many countries to develop prediction relations despite the complexity of this field, but they have shown several limitations and have fallen from general application. The following investigation will consider the best-known methods in this field and their validity.

One of the earliest studies was made by the Building Research Station in the London area (Fisk *etal*., 1974). This study examined the hourly values of L_{10} dB(A) in terms of some traffic parameters and a nearside building facade. All the sites consisted of built-up streets. The pattern of traffic flow varied from free to non-free. Eight hourly measurements were taken at each of the 23 sites included. The final Regression Equation was:

$$L_{10} = 49 + 11.5 \log_{10}Q + 0.14\ p - 11.5 \log_{10}d \qquad \text{... (4.17)}$$

where:

d = distance between nearside kerb and nearside building facade (m).

This method did not consider most of the design parameters and was based on limited survey sites.

Joyce, Williams and Johnson (1975) have also developed the following model for an urban environment:

$$L_{10} = 40.5 + 11.8 \log_{10}Q_w - 3.8 \log_{10}d \qquad \text{... (4.18)}$$

where:

L_{10} = Noise level at kerbside dB(A)

Q_w = Weight of flow (C+2L+15H+7B+2M)

C = Total flow of cars in both directions (v/h)

L = Total flow of light commercial vehicles in both directions (v/h)

H = Total flow of heavy commercial vehicles (over 30 cwt) in both directions (v/h)

B = Total flow of buses in both directions (v/h)

M = Total flow of motorcycles in both directions (v/h)

d = Distance from kerbside to centre of flow (m)

Joyce's model estimates the noise levels based on an hourly L_{10} dB(A) and traffic composition only. These limited parameters influence the prediction to an unacceptable degree as traffic composition alone is not sufficient for evaluating environmental noise in urban areas.

At present the most advanced model for predicting noise levels from interrupted traffic flow has been introduced by Gilbert *etal*.(1980). The model is based on a traffic noise survey in West London, which incorporated 17 sites. At each site eight 30-minute surveys were carried out between 7.00 and 18.00 hours, at one metre from the kerbside. The final model, which was developed by using the multiple regression analysis method was as follows:

$$\begin{aligned} L_{10} = {} & 43.5+11.2\log_{10}(L+9M+13M)-0.42C_w \\ & -10.2\log_{10}\left[\frac{d_k+3.5}{4.5}\right]^{\delta_1} \\ & +4.6\log_{10}\left[1+\left[\frac{d_k+3.5}{d_k+3.5+2(d_f-d_k)}\right]^{\delta_2}\right] \end{aligned} \quad \text{... (4.19)}$$

where:

L,M,H = numbers of light, medium and heavy vehicles respectively (v/h)

C_w = the width of the carriageway (m)

d_k = the distance from the kerbside to the receiver (m)

d_f = the distance from the kerb to the nearside building facade (m)

$\delta_1+\delta_2$ = ground cover indices defined as: $\delta_1 = 1+0.52\,p_1$ and $\delta_2 = 0.52\,p_2$. p_1 and p_2 are the proportion of soft ground between the kerb and the receiver and facade respectively.

This model employs large numbers of variables compared with previous methods. But again, it has not covered all the significant parameters which formalise the environment in built- up areas. The values of p_1 and p_2 are mostly zero in urban areas as they relate to soft ground only.

To summarise, most of the existing prediction techniques for noise arising from non-steady flowing traffic, utilise multiple regression analysis methods. Of these, the most advanced model was developed by Gilbert *etal*.(1980). But these methods have not proved their ability to assess this particular kind of environmental noise, because the problem of examining the behaviour of the noise level is made more difficult by the fact that there are complex interrelations between the large number of variables.

Existing methods have shown the following limitations:

(1) The speed of traffic: this plays a vital part in any road scheme. In urban areas, speed is significant in connection with traffic management, planning and road design (see Section 3.3.2.3).

(2) They disregarded the presence of various kind of junctions: in built-up environments junctions are the most essential feature in any development (see Section 3.3.1.1).

(3) They did not take into account the existence of surrounding building facades, especially those on the farside: in urban and suburban areas, normally the buildings are close to both sides of the road and hence cause noise reflection (see Section 3.3.4).

(4) They are based on a small number of survey sites which without doubt represent only a limited number of possible cases. The reliable model should satisfy a wide variety of built-up area conditions, e.g. various land use.

(5) They use L_{10} as a noise index while L_{eq} has received little attention. In view of the wide use of L_{eq} in Europe and the recommendations of the Noise Advisory Council (1978) it is beyond doubt that L_{eq} must be held up for comparison with other methods in the appraisal of noise from non-free flowing traffic.

(6) Planners, road designers and traffic engineers require prediction models which rely on current transportation engineering standards.

4.6.2 Theoretical models

A number of models have been established to predict the characteristics of traffic noise using other means. For example, an analytically derived model was obtained by fitting equations to field measurements of traffic noise. One of the earliest studies was the model constructed by Johnson and Saunders (1968). The model assumed a number of equally spaced identical vehicles all travelling at the same average speed on a single lane straight roadway. Each vehicle is considered to have the same acoustic power output. The model is to calculate L_{50} dB(A) from the perpendicular distance to the road, the flow and mean speed. The main disadvantage of this model is that it assumed the relationship of traffic noise level with mean speed was the same as for maximum sound levels from a single vehicle. This model has not been generally used because it has several drawbacks. One such drawback is that the model does not allow for the mixture of various vehicle classes based on the noise output of the different types of vehicles. This, among other things, makes it unsuitable for predicting noise from urban traffic in non-free flowing situations.

Models based on the statistical distribution of noise and traffic parameters have received some treatment in the literature. Takagi *etal*.(1974) developed a model which assumed that vehicles were point sources of equal acoustic powers and were distributed on an infinite line in such a way that the spacing between successive vehicles had a probability density function of an exponential distribution type. Kurze (1974) also established a model based on statistical properties of the noise from freely flowing traffic. Approximate formulae are presented for the distribution of sound level close to straight and unobstructed roadways. Again this type of statistical model has little application and in no way is non-free flowing traffic taken into account.

Computer simulation models have been derived by a number of authors. In particular, Galloway *etal*.(1969) issued a model to predict noise levels generated by freely flowing traffic. The model considered a random distribution of vehicles along a roadway of any number of lanes. This model proved to be valid for freely flowing situations. Nelson (1973) also developed a computer model for determining the distribution of noise from traffic. He introduced basic prediction equations similar to Delany's models. The results have been found to give reasonable agreement with observed values. In the USA, a design guide for prediction and control of highway traffic noise was established (Kugler *etal*., 1976). The guide contains a computer program method limited to free flowing traffic.

A remarkable number of computer models have thus been introduced to assess noise from freely flowing traffic. However, for noise from non-free flowing traffic in urban and suburban areas, a limited number of computer simulation models are available. Favre (1978) presented a computer simulation model which incorporates some of the characteristics of built-up areas, e.g. noise from acceleration and deceleration of traffic in the vicinity of traffic lights. The model uses empirical methods (regression analysis) established from field measurements. It is a step forward in this field but it has unknown validity, in addition to which it concentrates on traffic lights only. A similar study has been published by Jones and Hothersall (1980) on the effect of noise emission from individual road vehicles. By combining a scale model, empirical methods and computer simulated traffic flow, a prediction model was presented by Jacobs *etal*.(1980) for situations of free flow traffic conditions and for flow interrupted by traffic lights. The study concluded that if a traffic light is introduced, the value of L_{eq} rises compared with the free flow case.

The available knowledge indicates clearly that there is no comprehensive and practical computer model in current application for prediction of traffic noise associated with non- free flowing traffic. The main reasons are probably that non- free flowing cases in urban and suburban areas incorporate different land use classifications, variations in the level of noise, variations in output noise of each vehicle and other obvious features. These reasons combined thus give rise to the difficulty of formalising the background of the computer models.

To summarise, there are a considerable number of models introduced on the basis of theoretical assumptions. They are based on the statistical distribution of the noise, road and traffic features or computer simulation. Unfortunately, none have attained common application, because they do not accurately represent the everyday behaviour of road traffic in built-up environments. Apart from computer simulation models for noise at the approach to traffic lights, there is no comprehensive method in the field of non-free flowing traffic.

This study has introduced a computer model capable of assessing and predicting road transport noise under a variety of field conditions (Chapter 9).

4.6.3 Scale models

In real life, it is sometimes difficult to measure situations that concern particular specifications, e.g. the effect of ground surface. Thus, scale models have been introduced as an instrument in assessing the influence of specific variables without the need to take field measurements. Delany, Rennie and Collins, (1972c) have developed a 1:30 scale model for investigating the propagation of noise from freely flowing traffic on major roads and motorways. An air-jet noise source was used and the model was located in a anechoic room. The effects of air absorption were removed by correction of the measurements made in the model instead of using air drying systems. However, there is no scale model in general use for noise from traffic in built-up areas.

4.7 THE NEED FOR FURTHER INVESTIGATION

The relationships between traffic and the characteristics of built-up areas, environmental noise and people responses are not yet fully understood.

In recent years, the increasing emphasis on the abatement of road traffic noise has not resulted in a reliable prediction method to evaluate its effects in urban and suburban environments (Section 4.6). For example, current prediction methods have resulted mainly in regression or computer models which showed several performance limitations such as: neglect of design elements; small number of independent variables and conditions; concentration mainly on L_{10} as noise index; gave large error margin; and inadequate for practical situations which need detailed information(Section 3.4).

In addition, little has been known of the influence of the independent features (Chapter 3) on the level of noise in restricted flow situations. For example, the effects of frequency of junctions, which represent a most important part of urban design have received little treatment in the literature. There are also still many ununanswered questions in connection with traffic composition and traffic flow which are of changeable natures and depend on predictable (e.g. congestion) and unpredictable factors (e.g. accidents). Also, there is a need to assess the effect on noise level of adjacent building facades under various conditions. Studying the influence of traffic speed is necessary, since speed tends to be one of the dominant factors in the design of urban road networks.

Lack of knowledge even extends to the relationships between the influence of noise environment and its independent parameters on the individual and the public (Chapter Eight).

Therefore, study of traffic noise characteristics, e.g. junctions and facades, and development of comprehensive prediction models for noise exposure and noise annoyance will certainly advance the state of knowledge in this field.

4.8 SUMMARY

This chapter has been concerned with a review of the present state of prediction methods for road traffic noise.

Traffic noise in built-up situations is complex due to large number of interrelated variables. Its principal sources are the individual operations of many vehicles, travelling in various conditions at changeable speed through different road configurations surrounded by buildings.

The 'A' weighted sound level has become the standard scale on which to record traffic noise. Design rules for L_{10} and L_{eq} dB(A) are available, whilst other noise indices have not yet received recognition.

Large numbers of physical and social surveys have been carried out in many countries to assess the environmental effects of road traffic noise, and their results vary according to the method and objective of each investigation. Since the recommended individual vehicle noise limits are not based on people's response, other recommendations for traffic noise levels in outdoor and indoor environments have been made.

There has been slow progress in minimising vehicle noise at source and it is obvious that traffic noise surveys are time consuming and require skilled staff and expensive equipment. Consequently much work has been put into developing models for predicting the level of noise in terms of the independent variables.

Most prediction techniques in current use are based on free flowing traffic, using regression analysis, computer or scale models. By comparison no satisfactory methods of predicting noise from non-free flowing traffic in urban and suburban areas are in common use. Existing methods show several limitations, either because they neglect significant design parameters or because they are based on insufficient field work.

A clear need exists for a comprehensive prediction models to be employed by planners and designers to estimate and predict noise levels in their environments.

For the purpose of this study traffic noise indices, i.e L_{10}, L_{50}, L_{90} and L_{eq} dB(A), and measurement and analysis techniques were identified. The most appropriate types of prediction models, i.e regression and computer models, were also selected.

PART TWO

DEVELOPMENT OF EXPERIMENTAL PROCEDURES

CHAPTER FIVE

TRAFFIC NOISE SURVEY OF BATH

5.1 INTRODUCTION

The objective of this chapter is to report the way in which the discussion of the previous chapters was translated into a viable set of measurement operations and how these operations were executed. The chapter includes information on the experimental procedures of this thesis. It is concerned with developing and applying effective techniques for collecting, organising and analysing the data.

In general, the main goal for carrying out any traffic noise survey is to establish a noise climate acceptable to the community. The survey usually provides the practical background for the development of regulations and ordinance, to control potentially noisy schemes. It also provides the basis for the consideration of environmental noise during the design of new structures or operations, as well as land use planning. The survey assists in the establishment of a reliable method of predicting the influences of noise on the public, due to possible changes in the characteristics of accepted system.

In order to cope with all phases of traffic noise abatement, the following steps are required:

(1) Examination of all urban and suburban land use to determine which areas need to receive the most treatment with respect to varying levels of required protection from noise.

(2) Consideration of which noise sources are responsible for complaints in various areas and to what degree.

(3) A wide range of objective measurements must be drawn on, to evaluate the character and level of existing noise as well as to obtain the components of Prediction Models.

(4) Subjective measurements must be taken into account to evaluate various aspects of human reaction to noise as well as to assess the interconnecting relationships between people's reaction and independent variables of the surrounding environment.

The survey of traffic noise in the city of Bath was therefore carried out with a view not only towards investigating noise conditions, but also towards formulating a basis for prediction and evaluation of urban and suburban traffic noise associated with non-free flowing traffic.

In this chapter the following subjects are included:

(1) Planning of experimental procedures
(2) The characteristics of urban areas of Bath
(3) Areas covered by this study
(4) Location of measurement sites
(5) Traffic noise measurement and analysis
(6) Preliminary Field Study
(7) Results of 18-hour surveys
(8) Variables of interest

5.2 PLANNING OF EXPERIMENTAL PROCEDURES

Carefully collected data are the foundation of any soundly constructed project. To be sure that the data will be relevant, it is essential to establish the general objectives of the study, specify the elements to be observed and their relevant properties, and develop an appropriate technique to consider a wide range of elements.

Studying environmental noise which results from the operating characteristics of road networks in built-up areas is not an easy task because of the wide variability in the numerous contributory factors such as intersections, building facades and traffic composition. The initial step, therefore, was to select an area convenient for field work and to design a technique that would be capable of collecting and analysing data from real situations.

In order to resolve at an early stage the expected difficulties, a pilot study was set up. Selected places were examined, and in the light of the lessons learned in the pilot study, the main study was designed.

A procedures for the experimental investigations that are applicable to noise control systems was described in Section 1.2 and Figure 1.2. The goal was to construct models to represent the system under study, to test the models and estimate their practical application. The suggested procedures will be explained in this and the next chapters.

5.3 THE CHARACTERISTICS OF THE URBAN AREA OF BATH

5.3.1 City of Bath

Bath is a city situated on the River Avon with a population of about 102,000. It is one of the most beautiful cities in Europe, once a fashionable spa and now its magnificent Georgian architecture and Roman Baths are world famous (see Plate 1).

In Great Britain, Bath is regarded as one of the most important cultural centres and is acknowledged nowadays for its contribution to the art of urban design through its blending of historic buildings of such high architectural quality with modern buildings and shopping precincts. There exist in Bath powerful and vociferous conservation lobbies and so, for example, the marriage of the motor vehicle with other interests causes a great deal of conflict.

As well as architectural constraints, the topography inhibits planning and control of road traffic. The city centre is situated within a loop of the River Avon which flows from east to west. The high ground surrounding the city forms the green hill setting for which Bath is famous, but creates for the planners the difficult problem of finding satisfactory and economical routes for road networks, Plate 2. The incline of the hills to the north and south has tended to cause the city to spread longitudinally from east to west along the Avon valley. The most important single feature in the topography of the city is the tongue of land that extends south into the loop formed by the river from the high ground north of the city centre. This forms the site of the mediaeval city, some structures of which still remain. This feature constricts the flow of movement across the city in an east-west direction, and out of this there arises the most difficult planning problem in the city.

The relationship of Bath to neighbouring cities is shown in Figure 5.1. This also shows the River Avon, the traffic system, and the railways. The bustling city, port and airport of Bristol is only 12 miles away. Many trunk roads, such as the A4 and A46, pass through the heart of Bath, which also lies on the main Western Region railway line from London to Bristol and the southern railway line from Bristol.

5.3.2 Urban structure of Bath

The Romans first exploited the hot springs to make Bath a popular attraction and now the many Roman remains are of important archaeological interest (Figure 5.1). They are also a feature of enormous popular appeal, attracting many thousands of tourists annually. Many visitors to Bath come in their motor vehicles, providing the city planners and engineers with the problem of accommodating them, given the aforementioned architectural and topographical constraints. Features which have to be taken into account are:

(1) Development of the University of Bath (situated 2 miles from the city centre, a campus university with a population of about 5 thousand students and staff).
(2) City of Bath Technical College situated within the city centre.
(3) The central location of established cultural institutions and tourist attractions (e.g. the Festival, the Theatre Royal, and the Pump Rooms).
(4) The popular shopping area.
(5) The nationally and internationally linked transport services.
(6) The atmosphere of the old Georgian city and 28 places of interest.
(7) The landscape heritage which includes the surrounding hills.

City engineers are also continually faced with the need to take into account large numbers of everyday variables for different purposes, e.g. housing development, traffic demand and industrial construction. They must take all of these factors into consideration when planning a traffic scheme in order to:

(1) Meet the transportation needs of all users of the city centre, which have become a problem due to an increase of vehicle numbers.
(2) Promote efficient and convenient movement of goods and services within the central area.
(3) Reduce conflicts between pedestrians and traffic and create an attractive and safe pedestrian environment.
(4) Provide a supply of long and short term parking.
(5) Ensure the attractive and functional design of public areas.
(6) Ensure that nothing is erected nor any building altered in such a way as to damage the character of the city.

(7) Reduce the effects of road traffic on the individual and the public, such as noise, anxiety, fumes, vibration and visual intrusion.

5.3.3 Vehicular traffic and the environment

As with most modern cities, noise, air pollution and the various inconveniences caused by vehicular traffic bring with them high social cost and have a damaging effect on the quality of urban life. The twin aspects of 'environment and accessibility' can be conflicting ones. Where the environment is concerned, the important factors are ensuring freedom from danger; resolving the conflict between pedestrians and vehicles; noise, fumes, and vibration; visual attractiveness and protection of buildings. But regarding accessibility, the freedom of vehicles to move easily from one part of the city to another so as to have access to their destinations is essential.

Most of the environmental problems in the city arise from the presence of vehicular traffic and from the close spacing of the buildings which reduces the amount of daylight penetration. The amount of private and public open space between buildings is limited and the capacity to widen roads when necessary is minimised.

The Bath Planning Study introduced a concept for streets in historic areas where any street as it stands has an environmental capacity for traffic which must not be exceeded. On account of their intrinsic value, the streets cannot be widened or improved. Radical schemes such as the road or tunnel through the heart of the city were proposed in order to preserve the Georgian character of Bath and defend it against the effects of heavy traffic continuously driving through the heart of the city (Buchanan and partners, 1965).

The environmental consequences of excessive traffic can be seen very clearly on many roads and streets where there are large solid buildings. Noise , air pollution, and vibration caused by traffic have had very bad environmental effects, e.g. in London Road and George Street.

Another damaging effect of traffic is the visual intrusion of the vehicles either parked or moving, destroying the quality of space and view. Traffic lights, traffic congestion, danger and conflict between pedestrians and traffic constitute environmental impacts which have a negative effect on the value of property and the well being of the public.

5.4 Area covered by this study

Noise from road traffic exists all over the urban area but it is especially loud on roads and streets with buses, coaches and heavy lorries. Traffic is by far the most usual source of sound contributing to high noise levels. This aspect of the impact of traffic on the environment was selected as the subject of this study.

The study area was bounded in the north by the London Road- Gloucester Road intersection, in the east by Pulteney Road, in the south by Claverton Street, and in the west by the Upper Bristol Road. It was selected to give a wide range of the problems of interest. It contains the Abbey, the Roman Baths, central areas and the main routes. Most of the famous architectural structures of the eighteenth century lie inside the study area, Figure 5.1. Some sites were also chosen outside the above study urban area to include suburban conditions.

5.4.1 Land use

For the purpose of this study, six types of predominant land use were defined (see figure 5.2) as follows:

(1) Residential areas, e.g. The Circus, Julian Road and Great Pulteney Street.

(2) Shopping areas, e.g. Milsom Street and Argyle Street.

(3) Office areas, e.g. George Street and Pierrepont Street.

(4) Open space areas, e.g. Royal Crescent and Recreation Ground.

(5) Urban main road areas, e.g. London Road, Pulteney Road and Upper Bristol Road.

(6) Suburban principal route areas, e.g. Wellsway

5.4.2 Road network

The network of roads can be considered to fall into two areas, those concerned with junctions (node) and those concerned with stretches of road between junctions (link).

The main node types were defined as (Plates 3 and 4):

(1) Intersections controlled by traffic light signals

(2) Priority junctions

(3) Uncontrolled roundabouts

The considered links were either one-way or two-way systems. They fell into the following categories:

(1) Signal-controlled links

(2) Uncontrolled and give way links

(3) Roundabout links

5.4.3 Existing traffic situations

The main patterns of traffic in the city, Figure 5.3, can be considered as comprising:

(1) Heavy traffic conditions, such as on main roads which enable traffic to enter, leave or pass through the city with light, medium and heavy goods vehicles (see Plates 3 and 4).

(2) Medium traffic conditions, such as office, shopping and some residential areas with light and medium vehicles (Plates 5 and 6).

(3) Light traffic conditions, such as in residential and open space areas with light vehicles only (Plate 1).

This survey showed that most of the heavy traffic is concentrated on the main roads. There are trunk roads passing through the city such as the Upper Bristol Road, Pulteney Road and London Road and all of these roads are heavily loaded with traffic. London Road for example carries 2730 v/h. The A4 route which passes through George Street, Plate 7, in the heart of the city carries 1320 v/h but even narrow streets such as Pierrepont Street are heavily loaded with traffic. This street (an office area) carries 1192 v/h.

The public transport operations such as bus and National Express coach services depart from the bus station at Manvers Street in close proximity to the Railway Station at Dorchester Street, Plate 8. The buses serve the city and district while the railway and the coaches serve national and international routes. All coach and bus-routes pass through or start from the city centre and no street is reserved for bus traffic.

The shopping area has a wide range of traffic between 267 v/h along Milsom Street, for example, and 810 v/h in Argyle Street. There are two principal traffic conditions in the residential areas: either medium traffic such as at Julian Road or light traffic such as in the area surrounding the Circus. Open space areas have only light traffic conditions.

In accordance with the Bath Planning Study (Buchanan and Partners, 1965), the central pedestrian precincts were established. They are entirely reserved for pedestrians. The environment has been made more attractive by the addition of trees, flowers and benches, Plate 9.

There is public parking in the streets and in car parks. The permitted parking time differs from 20 minutes to 24 hours. The pedestrian precincts, car parks and bus station are shown in Figure 5.3.

The central pedestrian area is surrounded by a traffic zone. One-way traffic has also been arranged in such a way as to lessen conflicts at critical junctions by deflecting traffic away from some areas and to streets with sufficient width for two-way traffic.

5.5 LOCATION OF MEASURED SITES

A search was conducted in Bath for sites satisfying the objectives of the study. Approximately three hundred possible locations were identified. They were chosen to give a representative sample of traffic conditions for each of the six land use types. All the sites were typical of non-free flowing traffic. They were selected at varying distances from junctions. Only level stretches of roads were taken into account and the buildings flanking the roads were continuous on both sides (see Chapter 6 for more details).

The sites studied were classified as follows:

(1) 32 urban sites: field measurements were made at these sites for the purpose of preliminary investigations (see Section 5.7).

(2) 18 urban sites: these were chosen for the purpose of the 18-hour study, between 6.00 and 24.00 hours (see Section 5.8 and figure 5.9) to assess the noise level and to establish the measurement period of the main study.

(3) 172 urban sites: these sites were considered during the course of the main study. The measurement period was 12 hours at each of them, between 7.00 and 19.00 hours (see Chapters 6 & 7 and figure 6.1).

(4) 32 suburban sites: these were chosen to include the suburban region conditions. The measurement period was also 12 hours (see Chapter 7 and figures 7.1 and 7.2).

(5) 48 urban sites: these were selected from the above 172 sites to represent the social survey. The measurement period was extended to 18 hours, between 6.00 and 24.00 hours (see Chapter 8).

(6) Sites in various districts to evaluate the shielding and elevation of buildings as well as to test the validity of the developed prediction models (Chapters 7, 8 and 9).

44 junctions of various types were included in urban and suburban areas. These are: 23 intersections with traffic lights, 6 roundabouts and 15 priority junctions.

At each site, a study was made of the factors which were considered likely to affect the environment. Also each measurement location and each junction were given a reference number. More detail about the distribution of measurement locations will appear in the following sections and next chapters.

5.6 TRAFFIC NOISE MEASUREMENT AND ANALYSIS

It was necessary at an early stage of the research to standardise the measuring technique. This was firstly to avoid any false conclusions being drawn from the comparison of data obtained under differing conditions, and secondly, to connect the findings with previous practice. A comprehensive programme of experimental procedures was identified. It was decided that the programme should be capable of considering the normal behaviour of all the common variables in every day conditions. In the following subsections the most important aspects of the procedures are described. These include the practical details of the recording and analysis, the position of measurement with respect to the stream of traffic, the length of the tape recorded noise sample and the number of considered sites.

5.6.1 Recording and analysis procedures:

The traditional procedures for traffic noise measurement and analysis have been discussed in Chapter 4. The procedures have been well established (Department of the Environment, 1975; The Noise Advisory Council, 1978). These were followed in principle throughout this research. Most of the equipment used was manufactured by Bruel and Kjaer of Denmark. Detailed information on the machines is available in many acoustic publications (Bruel and Kjaer, 1975). The following principal items of equipment were employed:

(1) Precision sound level meter (B and K Type 2203), fitted with microphone (B and K Type 4145), and supporting stands.
(2) Sound level calibrator (B and K Type 4230).
(3) Windshield.
(4) Portable tape recorders (Uher 4000 Report L).
(5) Audio frequency spectrometer (B and K Type 2112).
(6) Level recorder (B and K Type 2305).
(7) Statistical distribution analyser (B and K Type 4420).
(8) Muniquip Digital Radar System, (Model, DRS-3) manufactured in Canada, for the measurement of speed.

Figure 5.4 shows the equipment used for the recording and analysis of road traffic noise. See also plates 10 - 12, and Appendix A.

During field operations, the basic noise data was obtained using a sound level meter mounted on a tripod with a microphone. The microphone was fitted with a windshield, to minimise the effect of wind without altering the acoustic characteristics of the instrument. The sound level meter was connected by means of a cable to a portable tape recorder. The equipment was set up in position, switched on, allowed to warm for half a minute, and then the battery conditions of the sound level meter and the tape recorder were checked.

The relevant data was noted on forms and also spoken onto the tape. Initially a 94 dB re 2 X $10^{-5} N/M^2$ calibration signal at 1000 Hz was applied for 1 minute to the sound level meter using the calibrator and recorded on linear weighting to check the stability of recording. The recording was then carried out for the appropriate length of time. A calibration check signal was applied at the end of the recording. During the recording, traffic was counted , the number of cars, lorries, and vans being noted separately. Speed was measured by a universal muniquip digital radar system mounted on a tripod. Other details of interest were recorded on the data forms. For the purpose of the simultaneous measurements, two sets of equipment were used, e.g. two sound level meters and tape recorders.

The analysis results were expressed in dB(A) which is standardised internationally (Hassall and Zaveri, 1979). While spoken information was checked with the written information on the data forms, the calibration signal was played into the audio frequency spectrometer and the level recorder was calibrated at the same time. The tape was run through the statistical analyser and set up for a specific time. After the analyser had stopped, the readings were noted. Different peaks on the level recorder graph could sometimes be identified whilst the analyser was in operation. The analysis was completed on site at specific hours. The process was repeated for each site.

The results of the survey could be used to give data on the levels of noise measured at each position. The readings of the statistical analyser were plotted on probability paper for calculation of noise levels. The values in dB(A) which were L_{10}, L_{50}, L_{90} were read from the curve for each measurement. L_{eq} was also analysed.

5.6.2 Position of measurement system

It has emerged from various field studies that the most suitable location for measuring noise levels in restricted flow situations was at a point close to the nearside kerb (see Section 4.4.3).

For this study, it was decided to carry out the measurements at 1m from the nearside kerb or at 1m from the nearside building facade. A series of measurements were also made at various locations between the nearside kerb and nearside facade.

This study covered up to 25m distance between the nearside kerb and nearside facade, while the distance of the farside facade was up to 36.5m (see next Chapter). But it was found that in the majority of cases (98%) the distance of the nearside facade from the road was within the range of 8m (see Figure 6.11). This finding was true of urban and suburban areas where the buildings were constructed closely on both sides of the roads. Besides, free choice to take a measurement at any distance from the road was not always available (Section 3.3.3). Moreover, evidence from the Pilot (Section 5.7) study and previous experience (Hood, 1986) have shown that there was no significant variation in the level of noise within 8m from a road surrounded by buildings on both sides. The main explanation is the influence of buildings on noise reflection (Section 3.3.4). So the majority of field measurements (e.g. the main study) were taken at one meter from the nearside kerb. The following points illustrate the advantages of measuring noise at one meter from the kerb.

(1) To avoid the difficulties which appeared when the measurement was located at 1m from the facade or at various distances between kerbside

and facade because of pedestrian activity, especially in shopping and office areas.

(2) To establish a common measurement factor between the various sites because of the difference in distance of building positions from the road network.

(3) Noise level at any site is dependent on related variables combined. So measurement at 1m was found most convenient especially when the effect of farside and nearside facades and other variables were considered.

(4) To establish a link with previous practice in this field (Chapter 4).

In addition, measurements were taken simultaneously at 1m from kerb and at 1m from the facade, to examine the relationship between noise level and distance from source, as illustrated in Section 5.7.4. Furthermore, measurements were conducted at 1m from the facade or at various distances from traffic to test the validity of the developed prediction models (Chapters 7 and 9).

For the purpose of this research, measurement at 1m from the road was found most convenient for the evaluation of noise level in built-up situations, especially when the effects of surrounding facades were taken into account.

In order to deal with individual cases or more complex or detailed situations, a computer prediction model was established. The model has the flexibility to measure noise level at any required distance, for example at 1m from the facade and 25m from the road (see Chapter 9).

5.6.3 Sampling of noise measurement

A decision also had to be made regarding the length of time for which the simultaneous recordings of environmental noise and independent variables would be measured. Of course, sampling error caused by variation in the effects of the independent variables decreases as the sampling time is increased (see Section 4.4.2). Thus, a balance had to be struck between obtaining a representative measure and taking into account the characteristics of the situation under study. In their earlier study, Johnson and Saunders (1968) suggested a minimum measurement period of 15 minutes. The Department of Environment (1975) design guide indicates that the minimum sample length leading to a valid measurement of L_{10} should not be less than 5 minutes, nor needs to be more than 55 minutes, in any hour. It also gives a recommendation for the minimum sample length, $t_{\min}$, based on the total flow-rate q in vehicles per hour, and the registration rate r in samples per minute : $t_{\min} = \frac{4000}{q} + \frac{120}{r}.$ The sampling error also has been estimated by Fisk (1973) to be : $\Delta\ L_{eq} = \frac{7.4}{\sqrt{m}} dB(A)$. Where m = the number of vehicles passing during the sample.

Six 30-minute samples were also examined. The samples were selected as representative of the three traffic conditions of the study area. Two samples were for traffic flow between 2500-3000 v/h, two samples for traffic flow between 1000-1500 v/h (medium), and two for light traffic conditions, between 500-1000 v/h. 5, 10, 15 and 30 minute periods from the 30 minute tape were repeatedly analysed, assuming the noise indices obtained from the 30-minute recording to be representative of the actual noise level. Study of the samples indicated the increase in scatter on the probability paper with reduction in the period of analysis. These results show that even for a 15 minute sample L_{10} values varied ± 2, from the 30-minute values. Thus, all measurements in this study have been taken in 30-minute samples. This has several advantages. It minimises sample error, covers many real conditions and makes it possible to apply accurate statistical analysis.

5.6.4 The number of considered sites

Concerning the number of sites to be covered, it has been seen that the most convenient method of investigating traffic noise is to directly measure the characteristics of noise generated by a range of road networks. From this investigation an empirical relationship can be derived to describe the process between the dependent (e.g. L_{10}) and independent (e.g. traffic flow) variables. The finding usually depends on the nature of the particular aspect of the situations under study and the relation of the characteristics to it. The statistical method that is often followed to measure the variables of a very large population is to use the technique of sampling (Berenson and Levine, 1983). This involves choosing a sample of the population (The population is the total collection of observations or measurements that are of interest to the statistician or decision-maker, while the sample is a subset of measurements taken from the population). These sample variables are usually employed as an estimation of the true population. Thus the method of sampling can be applied to this study by considering an adequate number of sites (or subjects in the case of the social survey - Chapter 8) as representing the conditions of traffic noise in urban and suburban areas.

Ideally, the sample should be selected with respect to all of the related variables of urban and suburban areas. But this was not easy because of the large number of variables involved. In addition, information was only available on some of the variables involved, as reported in Chapter Three. Furthermore, previous related practice was based only on a small number of sites and conditions, e.g. twenty three sites and three variables (see section 4.6.1.2), which without doubt represent only a limited number of possible conditions.

As far as this study is concerned, it was decided to play safe and select a relatively large sample. Thus, there are 172 or 204 sites (Section 5.5) which could be used in the construction of prediction models (next chapters), besides the consideration of 40 variables (section 5.9). The point of covering a large number of sites and variables is firstly, that increasing the number of the sites used in any regression model (sections 4.6.1 and 6.2) based on field study allows high accuracy of prediction, approximate to that which would exist if the sample was infinite. Statisticians have also found that for most population distributions once the sample size is at least 30, the sampling distribution of the mean will be normal (Berenson and Levine, 1983). 30-40 observations were cõnsidered adequate for constructing a linear regression model. Secondly, consideration of a large number of sites and variables is required (due to the unavailability of a reliable method) to establish a comprehensive prediction model, as forward planning in built-up situations has to rely on judgements taken with sufficient information.

The required sample size was also evaluated by using the following formulas (Berenson and Levine, 1983):

$$n_0 = \frac{Z^2 P(1-P)}{e^2} \qquad \text{... (5.1)}$$

and

$$n = \frac{n_0}{\frac{n_0 + (N-1)}{N}} \qquad \text{... (5.2)}$$

where:

$n_0 = correction\,factor$

Z = the confidence level desired

P = an estimate of the true proportion of population who are satisfied (P=0.5 when there is no prior knowledge or estimate of it)

e = the sampling error

n = sample size

N = population size

The adequate sample size was determined with 95% confidence level, p=0.5 and e=±5%. It was found that the required sample size was 169 out of 300 sites identified in urban and suburban areas (Sections 5.5), to satisfy the conditions of the physical measurements. So it is obvious that an adequate number of sites (172 and 204 sites) has been considered by this study to establish the prediction models (next chapters). Moreover, since this study was directed to estimate traffic noise associated with specific situations, effort has to be put into the selection of a site which reflects the required conditions (Collins, 1986), and this has been done (see Section 8.4 for more details of sampling technique).

Computer data files were created containing for each site a record of measured L_{10}, L_{50}, L_{90} and L_{eq} dB(A). They also included the following: mean speed; numbers of light, medium and heavy vehicles; road width; distance from surrounding building facades; distance from considered junctions and all other data of interest (Section 5.9).

Computer programs were then established to analyse the information on the data files. The statistical programs (Sections 6.2 and 8.4) utilised MINITAB and SPSS, while other programs (Chapter 9) utilised FORTRAN language and GINO-F graphic system.

5.7 PRELIMINARY FIELD STUDY

The objectives of the preliminary field study in urban areas were as follows.

(1) To furnish the background information which is currently lacking on the characteristics of noise generation variables.
(2) To identify the most effective variables to be considered by this study.
(3) It was important to provide familiarisation with the recording and analysis techniques.

(4) To establish working conditions which could be achieved over a wide range of urban and suburban environments.

Field measurements were, therefore, carried out as to the character and level of noise associated with different variables, especially for those variables needing more attention in order for their importance to be identified. 32 places were chosen for these objectives. Individual vehicle maneuvers were studied and a simultaneous recording of noise and independent variables was undertaken. The examination of light vehicles and the significance of some of the parameters which have previously been ignored by existing prediction methods are described below.

5.7.1 Maneuver of individual vehicles

Since the main goal of this study is to obtain an understanding of the noise emitted by interrupted traffic flow, it was felt necessary to identify the characteristics of noise generated by individual vehicles under various conditions.

Two vehicles were selected for the study, one of which was equipped with automatic transmission. The vehicles selected were:

(a) Opel Kadett, 1196cc, Reg. No. RYB 324R. Automatic, 2 doors and in good condition.

(b) Toyota Corolla, 1100cc, Reg. No. JHY 61P. 2 doors and in good condition.

Although they represent the quietest class in contrast with medium and heavy vehicles (Section 2.2), these light vehicles were chosen for the following reasons.

(1) One of the objectives of the primary study, as mentioned above, was to have some background knowledge of the characteristics of noise levels associated with built-up area situations, rather than to study the specifications of each class of vehicles.

(2) Light vehicles were available for the author, in view of the resources to hand, to examine the performance of noise levels under specific states only (in isolation from road traffic).

(3) The characteristics of built-up area driving, e.g. acceleration or squealing of tyres, affect the noise level from light, medium or heavy vehicles, despite the differences in the emitted level of noise which depend on the design and other conditions of each class. So it was believed that the use of light vehicles was appropriate.

(4) This thesis deals with the noise from road traffic (mixture of vehicles), as mentioned in previous chapters, rather than a specific kind of vehicle. So examination of light vehicles would not influence the final findings of this thesis, but provide initial knowledge of the main sources considered during the main study.

With urban traffic at a vehicle speed limit of 48 Km/h, among the modes of operation which generally create high noise levels are acceleration from junctions and squealing tyres. So it was believed that the following different situations have to be studied to understand the factors involved in changes of vehicle noise level.

(1) Stationary vehicle with the engine operating.
(2) Vehicle at steady speed of 48 Km/h.
(3) Vehicle accelerating from 0 to 48 Km/h.
(4) Vehicle braked hard at speed of 48 Km/h.

The investigation was limited to noise from vehicles at stop to cruise speed, measured externally and inside the vehicles.

Despite the interest in external motor vehicle noise reduction (Chapter 2), an area that has not been adequately studied is the characteristics of noise inside vehicles (Behar, 1981). Noise level inside vehicles usually affects the driver and passengers. For example, high levels may cause damage to hearing after long exposure of vehicle drivers, especially to the drivers of heavy lorries. Behar (1981) found that the range of noise levels inside the cabins of various lorries (new & old and various makes) was between 82-92 dB(A) at low gears and between 82-93 dB(A) at high gears. The measurements were made when the windows were closed and the microphone location was between the driver and the passenger at 75 cm above the seat. Behar gave no detailed information about the lorries studied, but the results indicate clearly the high level of noise inside the lorry cabin. Inside noise level is also required to be comfortable, especially with regard to speech interference and driver performance. The noise inside the vehicles is due to several factors. Priede (1980) confirmed the engine, vehicle speed and air buffeting at speed above 80 Km/h. Whether the windows are open or closed affects the level of noise. Noise inside the vehicle is also produced by vibration of the internal surfaces of the vehicle. Although it is not the subject of this thesis, it was felt beneficial to have general information on the performance of such noise under various vehicle operating conditions, which occur often in built-up areas.

There is no common method of measuring inside vehicle noise (Behar, 1981), although the SAE Standard recommended that the microphone must be situated close to the driver's right ear, for a lorry cab (American National Standards Institute, 1971).

The measuring position of this study was situated in the middle of the cars, as it was believed it is more representative in the case of passenger cars.

An upper limit of 48 km/h was employed. The driving was confined to those areas on Bath University Campus where a level road surface existed. The distance between the microphone and the sound source was 7.5m (ISO, 1964), in the case of external noise. There were no building facades flanking the measurement sites. The characteristics of spectra shapes for external noise levels and the characteristics of noise inside the vehicles are shown in Figures 5.5 and 5.6, for vehicles in the following states: stationary, steady speed, acceleration and brake.

It was noticed that the highest acceleration noise level occurred when vehicles reached a speed of 40 Km/h. This was also found at 45m from starting line (speed = 0 Km/h). So the measurement point was situated at 45m from the starting line to measure the external acceleration noise. In order to measure the noise level when the vehicles were moving at a steady speed (48 Km/h), a second measurement point was located at 250m, from the starting line. The measurements of squealing tyre noise when the vehicles braked hard at 48 Km/h, were also undertaken at 250m. The 250m range was selected to guarantee the influence of stable cruising speed. Measurements inside the vehicles were also carried out under the same conditions.

It is clear from Figure 5.5 that a difference exists between the range of spectra from stationary to acceleration and brake conditions. However, the squealing of tyres in Britain is not important in the context of the total noise produced by traffic (Ratcliffe, 1987), whereas, in some countries such as the USA and Canada, this kind of tyre sound is more significant, especially near road junctions. This is true of large cars and heavy lorries. The reason for this is that the pattern of traffic and method of driving are some what different in these countries. For example, heavy lorries in Britain are smaller and tend to travel slowly. Motor vehicles are generally driven with more consideration in Britain than abroad. Similarly, Figure 5.6 shows that there was also a difference between steady speed and acceleration and brake states. This finding also referred to the fact that acceleration and stop-start situations occur very often when the vehicles operate at speed below 48 Km/h in built-up areas, which can lead to high noise levels.

It is clear that a prevalence of sound levels exists at low frequencies, below 200 Hz. The trend towards high levels at low frequencies has also been found by other researchers (Galloway *etal*., 1969), for passenger cars and diesel lorries. The low frequency sound was believed to be responsible for people's annoyance and gave high correlation with people response (Hollingworth, 1980; Watkins, 1981).

The only cures for vehicle noise are the obvious ones of, firstly, attention to the design of the vehicle itself, as reported in Chapter Two, and secondly, separation of vehicles and people through planning and design, as stated in Chapter Three.

This thesis deals with the second point above for noise from a stream of traffic. So further investigation of the single vehicle noise (inside and outside) has not been undertaken during the course of main study.

However, the limited field study of this subsection reflects the factors involved in variation in noise level, which usually occur in built-up area of non-free flowing traffic to which this thesis was directed.

The acceleration, squealing tyre and traffic compositions, as an independent variables, were covered by the main study (next chapters).

5.7.2 Location of junctions

Simultaneous measurements of sound levels at different distances from traffic light intersections, roundabouts and priority junctions were made. The intersections were selected as the reference position, in order to measure the level of noise along their arms. The reference position was the nearest corner, since recording at the centre of junctions was impossible. (see Figure 6.22 and 6.25). Ten sites were selected, representing a variety of land use and traffic conditions. Building facades were not more than 8m from the nearside kerb, (see also Table 5.1).

The regression relationship between noise level and distance from junctions (J) was:

$$L_{10}=82.0-0.0215J \qquad \text{... (5.3)}$$

where:

R = -0.73

St.dev. = 2.1

The above formula indicates that the noise level is reduced for each increase in the distance from the junctions, as shown in Figure 5.7.

It is obvious, for example, that the noise level decreased from 81.914 dB(A) at 4m to 79.85 dB(A) at 100m (2.1 dB(A)). This result reflects the degree of participation of various junctions in maximising the magnitude of the noise, although the range of influence of various junctions on noise level was found to be dependent on many factors, e.g. length of stretch of road between junctions. So distance from various junctions was considered during the main study (next chapters).

5.7.3 Speed of traffic

The relationship between noise level and the mean speed of passing traffic was found as follows:

$$L_{10} = 84.1 - 0.123V \qquad \text{... (5.4)}$$

where:

$R = -0.560$

St.dev. = 2.490

The above formula was based on the recording of noise level, speed and other required independent variables at ten sites (see Table 5.1). It is clear that noise decreases with increasing speed, unlike noise of free flowing traffic. This relation also depends on many other related variables.

It was decided, therefore, to consider the speed of traffic during the procedures of the main study (next Chapters).

5.7.4 Location of building facades

Ten sites were selected at various land use areas and with different distances between the building facades and the traffic as illustrated in Table 5.2. Road surfaces were dry asphalt with no gradient, while the buildings were continuous on both sides. Simultaneous measurements were made at one meter from the nearside kerb and one meter from the nearside building facades, see Figure 5.8.

Site No.	L_{10} dB(A)	V (km/h)	J (m)	Measurement No.
1C	83.0	13	4	1
2C	83.8	32.4	50	(traffic light)
3C	83.5	25.5	25	2
4C	82.0	40.1	100	(roundabout)
5C	79.0	15.5	8	3
6C	77.5	49.3	160	(roundabout)
7C	80.0	31.6	40	4
8C	75.3	50.1	310	(traffic light)
9C	80.0	21.6	6	5
10C	78.0	38.9	120	(priority junction)

Table 5.1 Simultaneous measurement of noise level L_{10} at different distances from five junctions (accelerating traffic under various conditions). J = distance from junction, V=mean speed of traffic.

Site No.	L_{10} dB(A)	Distance from nearside kerb (m)	Measurement No.
1B	79.3	1	1 (d=21)
2B	74.0	20 [1m from the facade]	
3B	76.0	1	2 (d=23)
4B	72.0	22 [1m from the facade]	
5B	77.7	1	3 (d=18)
6B	73.8	17 [1m from the facade]	
7B	78.0	1	4 (d=24)
8B	71.5	23 [1m from the facade]	
9B	82.0	1	5 (d=8)
10B	81.9	7 [1m from the facade]	

Table 5.2 Simultaneous measurement of noise level L_{10} at one meter from the nearside kerb and one meter from the nearside building facade under various conditions. k= The distance between measurement point and nearside kerb (m). d=The distance between nearside kerb and nearside facade (m)

Site No.	L_{10}dB(A)	K(m)	Traffic conditions	Measurement No.
13B	82.8	1	Heavy (Pulteney Rd.)	1
14B	82.9	5		(d=6)
15B	81	1	Heavy (Pultney Rd.)	2
16B	81.2	5.5		(d=6.5)
17B	83.2	1	Heavy (London Rd.)	3
18B	83	6.5		(d=7.5)
19B	79	1	Medium (Charles St.)	4
20B	78.9	6.5		(d=7.5)
21B	81.5	1	Heavy (Upper Bristol Rd.)	5
22B	81.5	7		(d=8)
23B	83	1	Heavy (Lower Bristol Rd.)	6
24B	82.8	7		(d=8)
25B	78	1	Medium (Dorchester St.)	7
26B	78	7		(d=8)
27B	76.5	1	Light (Lower Oldfield Park)	8
28B	76.5	7		(d=8)

Table 5.3 Simultaneous measurement of noise level at nearside kerb and nearside facade under maximum facade distance (d) of 8m.
k = The distance between measurement point and nearside kerb
d = The distance between nearside kerb and nearside facade (m)

The regression relationship between noise level (L_{10}) and distance between kerb and nearside facade (d) was (Sites 1B, 3B, 5B, 7B, 9B):

$$L_{10}=84.1-0.291d \qquad \text{... (5.5)}$$

where:

R = -0.840

St.dev. = 1.40

The formula shows that the noise level is reduced for each increasing of the distance of the facade from the road.

It was also concluded that there is no significant decrease in noise level when the distance between the nearside facade and nearside kerb was up to 8m. Table 5.3 shows the results of simultaneous measurements at various distance from road under different conditions. The correlation coefficient of L_{10} and d (Sites 13B, 15B, 17B, 19B, 21B, 23B, 25B, 27B) was R=-0.393, while St.dev. was 2.50.

For the purpose of the main study, the farside and nearside facades were considered (next Chapters).

5.7.5 Summary of the preliminary study

The preliminary study was executed by undertaking field measurements at selected urban sites of various conditions.

The preliminary study assisted in familiarising with and facilitating the procedures at sites in built-up situations. These include the use of recording equipment in streets where there were many pedestrians, and experience in analysis of findings.

The study confirmed the influence of vehicle performance in built-up areas on the level of emitted noise, especially acceleration and the squealing of tyres. Relationships were also found between noise level and the distance from junctions, the speed of traffic and the building facade. These relationships at least identified such variables as contributing to the level of noise, in spite of the low level of correlations and the difficulty of assessing their individual influence in isolation from the other contributing variables. They were therefore considered during the process of the main study.

The overall variables of the main study were selected on the basis of the knowledge obtained from the preliminary study, and the conclusions of previous chapters (Section 5.9).

5.8 RESULT OF 18-HOUR SURVEY

It was decided to conduct an 18-hour survey at limited numbers of sites which were chosen as representative of various conditions. The main objective was to define the period of noise annoyance in the study area.

Eighteen sites were chosen for hourly measurements between 6.00 and 24.00 hours, Figure 5.9. It was assumed that the 18 hour survey would give a representative picture of the actual noise level occurring in the urban area. Different types of land use were selected for each of these sites. The area surveyed included many typical main roads, shopping, office, residential and open space areas, including the bus station, shopping centre, railway station and main buildings. Measurements confirmed that the predominant noise by day was due to road traffic. As expected the points in the higher noise level range were on extremely busy roads (e.g. London Road) carrying heavy traffic, whereas those in the lower range were on the streets carrying light traffic (e.g. Royal Crescent). In the majority of cases there were peaks in noise in the morning and afternoon. Most central area streets showed a marked increase in noise levels at rush hours (e.g. High Street and New Bond Street). Roads most likely to show an increase in noise levels were those used as alternative routes when the main routes became overcrowded. An example of this was the Circus which was used as a short-cut when George Street and Julian Road became very busy. In addition, most streets which led to main roads became noisy at these times (e.g. Paragon and Walcot Street).

The results of the survey showed the variations in the character and level of noise from site to site and hour to hour. They showed that there was a distinct daytime period from 7.00am to 7.00pm when noise increased to produce the highest noise levels, and a night time period from 7.00pm onwards which can be categorised as producing the lowest noise levels. Noise levels dropped to a minimum during the early hours of the morning. After 7.00 am the noise increased sharply as the daily activity of the city commenced.

On the typical main roads, the results of the 18-hour surveys are shown in Figure 5.10. The hourly variations in noise level (L_{10} dB(A)) and other indices clearly reflect the volume of traffic and high proportion of heavy vehicles which were passing along these roads. The levels peaked at 9.00am and 5.00pm, the morning and evening rush hours; minimum levels occurred in the early morning hours.

Figure 5.11 for the shopping centre shows increased values of noise levels after 7.00am. There is continuous activity during weekdays with peaks at 12 noon, 2.00pm and 5.00pm, with a drop in the level of noise after 7.00 p.m (see Plate 5).

The light traffic residential site was located near the shopping centre and the typically high and low noise levels are again clear in Figure 5.12. The influence of shopping centre activity is very marked (see Plate 1).

The survey showed that the increase in noise levels due to heavy and medium traffic started to be apparent from 9.00 am through to 7.00 pm when the levels dropped considerably.

In general, it has been found that the 'noise day' extends from 7.00 am to 7.00 pm. Thus it was decided to limit the survey to 12-hour measurements, between 7.00 and 19.00 hours, except the social study. This period is also appropriate for the evaluation of traffic from the traffic engineering point of view. It covers the morning and afternoon rush hours which are essential for the estimation of daily and weekly or annual volumes of traffic (Phillips, 1979).

5.9 VARIABLES OF INTEREST

Previous sections have described the principal procedures which are necessary preliminaries to the main study. This section involves the final step which revolves around the collection of suitable data, since numerical data is the raw material of any traffic noise survey. Without a reliable data base, forward planning has to rely on judgements taken without sufficient information.

Traffic noise variables (noise indices) and related independent variables were defined in Chapters 3 and 4. It has been shown that it may be possible to define the values of noise indices if their dependence on other factors (independent variables) can be determined. The main reason for this was to develop suitable prediction methods for planning and design purposes as well as to estimate subjective responses, in order to define the best noise climate for the community.

With the above practical constraints, the final step in the design of this study was to determine what variables were to be included in the analysis.

Ideally, traffic noise should be measured with respect to all of the relevant independent variables. But this was not possible because of the large number of variables formalising the urban and suburban environments and because information was only available for a few of them. However, in view of the preliminary investigations, it was decided to include as many variables as possible, since the essential goal of this study is to establish comprehensive prediction models.

40 variables which fall in two main families were eventually considered (in addition to the social survey variables - Chapter 8). The first family consists of the characterists of the noise itself (the dependent variables) while the second family consists of characterists of road, traffic and surrounding structure (independent variables). The specifications of many of these have been discussed earlier. The selected dependent variables are the well-known noise indices while the independent variables have been chosen for the following reasons:-

(1) They affect the generation and propagation of noise levels.
(2) They are necessary to the work of designers and planners.
(3) There is a need for further research into several features of traffic noise in interrupted flow situations.

5.9.1 The dependent variables

Four dependent variables of road traffic noise were chosen as follows:

(1) L_{10} dB(A)
(2) L_{50} dB(A)
(3) L_{90} dB(A)
(4) L_{eq} dB(A)

5.9.2 The independent variables

These are all the independent variables commonly used. They include the 'basic variables' (e.g. quantifiable variables such as speed) and the 'descriptive variables' (e.g. unquantifiable variables such as residential areas). See also Section 9.3.

5.9.2.1. Traffic variables

(1) Traffic flow

(2) Traffic composition: the vehicle classes were defined as (Nelson and Piner, 1977):

- (a) Cars, vans and light goods vehicles<3000 Kg unladen weight
- (b) Medium goods vehicles with two axles>3000 Kg unladen weight, including buses and coaches
- (c) Heavy goods vehicles which include all commercial vehicles with three or more axles

(3) Percentage of heavy and medium vehicles

(4) Traffic speed

(5) Traffic conditions (i.e light, medium and heavy)

(6) Traffic status (i.e accelerating and decelerating traffic)

(7) Traffic directions (i.e one-way and two-way traffic)

5.9.2.2. Road variables

(1) Road width

(2) Distance from road junctions

(3) Number of lanes (i.e two, four or more)

(4) Condition of road surface (i.e asphalt or concrete)

(5) Type of junctions (i.e traffic light, roundabout or priority junction)

5.9.2.3 Land use variables

(1) Residential areas

(2) Office areas

(3) Shopping areas

(4) Open space areas

(5) Urban main road areas

(6) Suburban principal route areas

5.9.2.4. Building variables (Propagation variables)

(1) Distance between measurement point and nearside building facade

(2) Distance between measurement point and farside building facade

(3) Distance between measurement point and nearside kerb

(4) Height of measurement point

5.9.2.5. Weather variables

(1) Wet weather

(2) Dry weather

(3) Windy weather

These variables will be estimated and employed during the design of prediction models (next Chapters).

5.10. SUMMARY

The chapter has outlined the procedures of this research development. The study area has been described. Six types of land use have been defined at urban and suburban sites, chosen as representative of the kind of traffic conditions at each of these sites. All the sites were typical of non-free flowing traffic and at varying distances from signalised intersections, priority junctions or roundabouts. The buildings were continuous on both sides of the road network. Techniques of data collection and analysis were described. Noise measurement at 1m from the nearside kerb was found to be the most convenient. 30-minute measurement samples were recommended for all measurements. Preliminary field investigations to assess the significance of related variables have also been reported. The findings of the 18-hour surveys indicated that the period between 07.00 and 19.00 hours (12 hours) was suitable for the purpose of this study. The variables which have been estimated and employed by this study have been listed. They cover traffic, road, land use, building and weather variables.

In view of the subjects reported in this chapter, the background knowledge obtained from the preliminary study and the conclusions of previous chapters the main study was executed (next chapters).

Fig. 5.1 LOCATION OF BATH

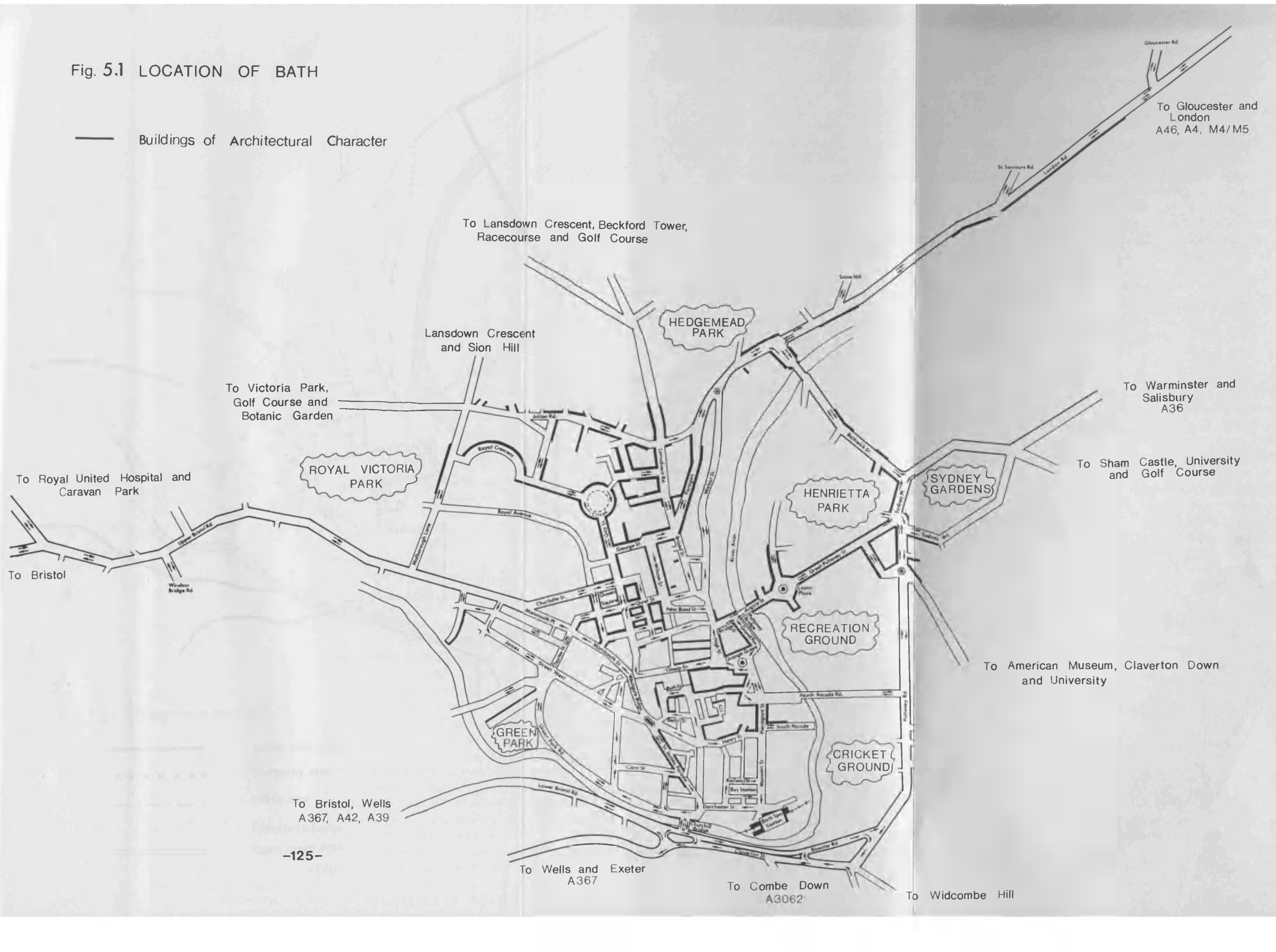


Fig 5.2 Predominant land use

Main road area

Shopping area

Office area

Residential area

Open space area

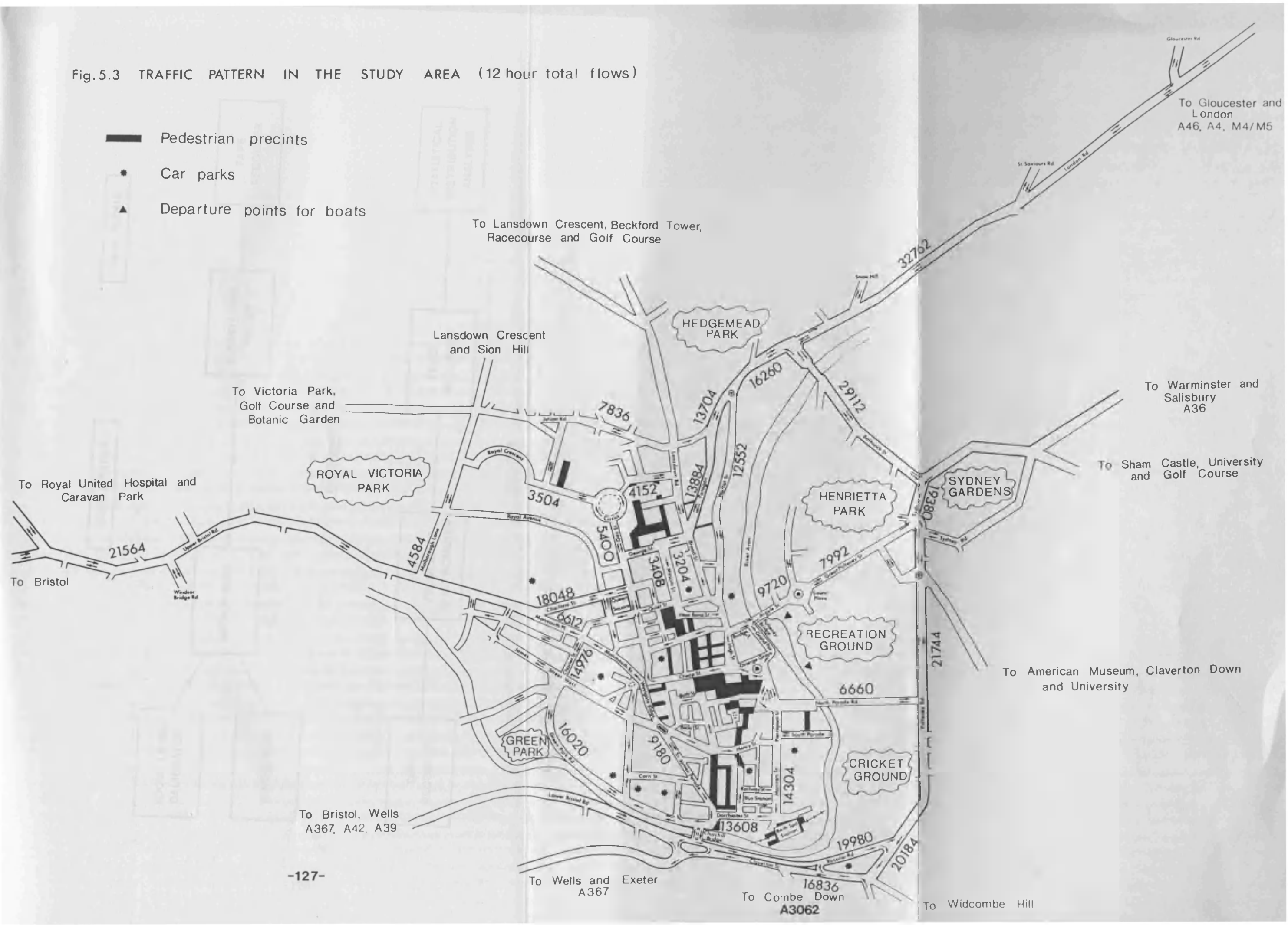


Fig. 5.3 TRAFFIC PATTERN IN THE STUDY AREA (12 hour total flows)

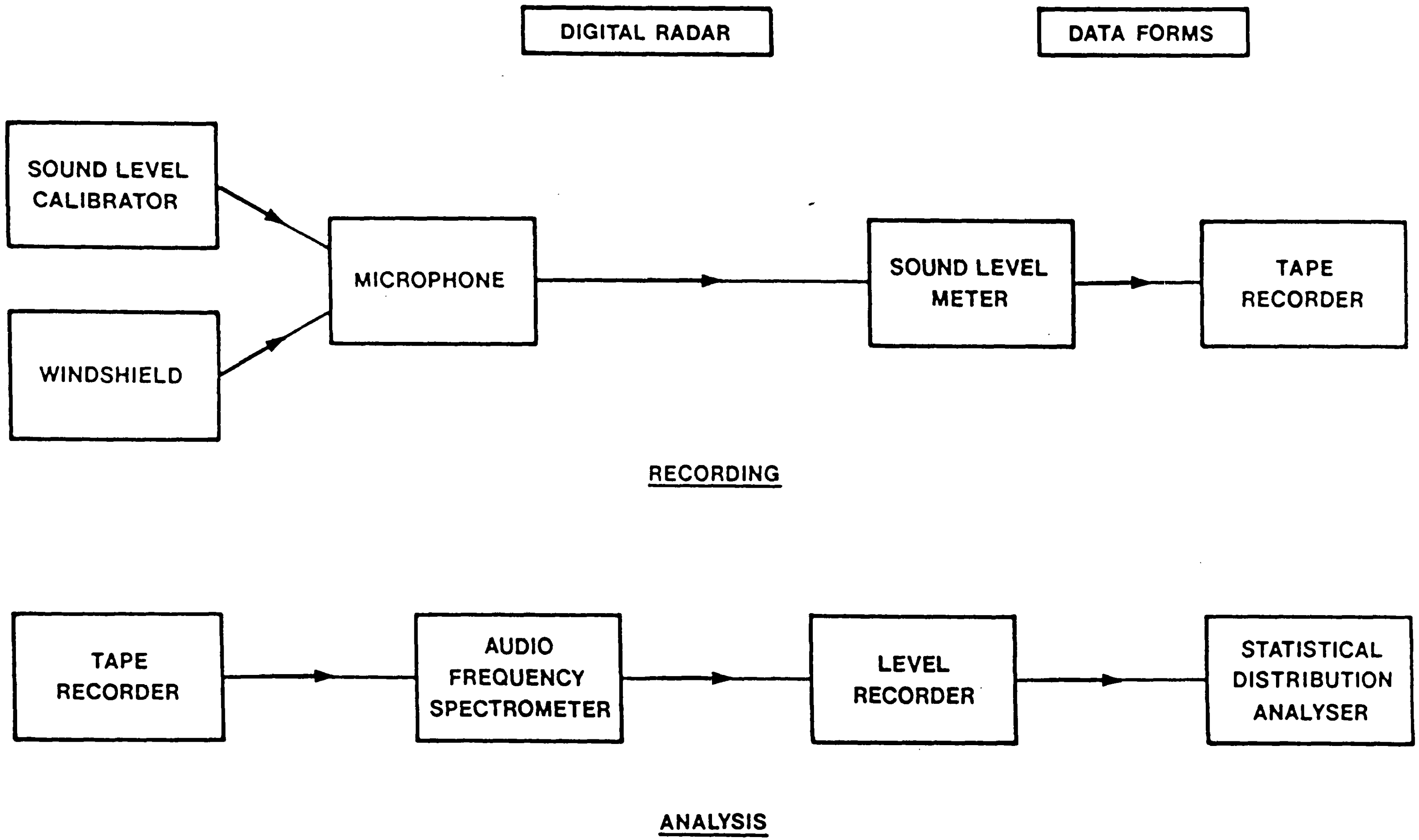


Fig 5.4 Equipment used for the recording and analysis of road traffic noise

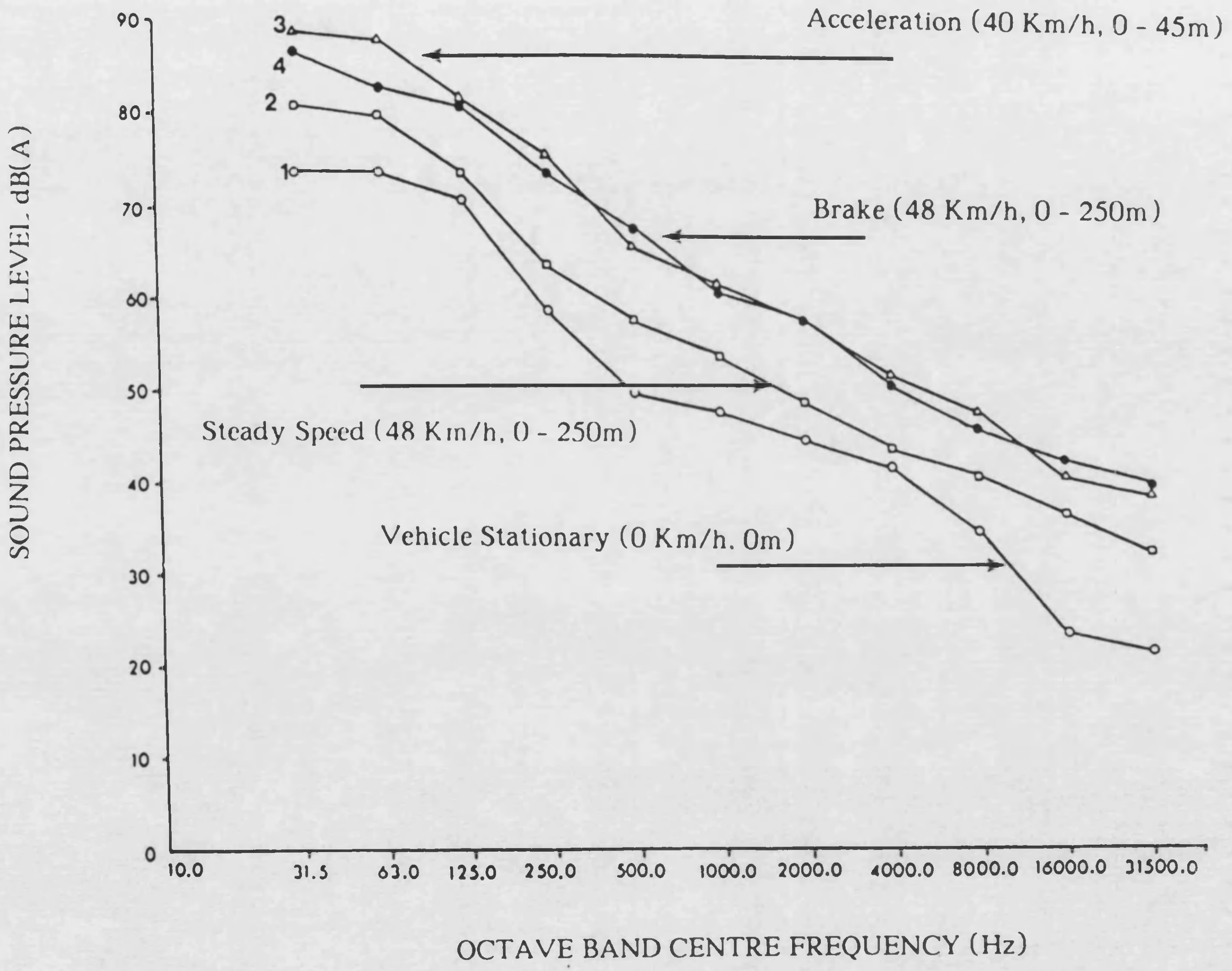


Fig 5.5 Characteristics of noise spectra outside the passenger cars

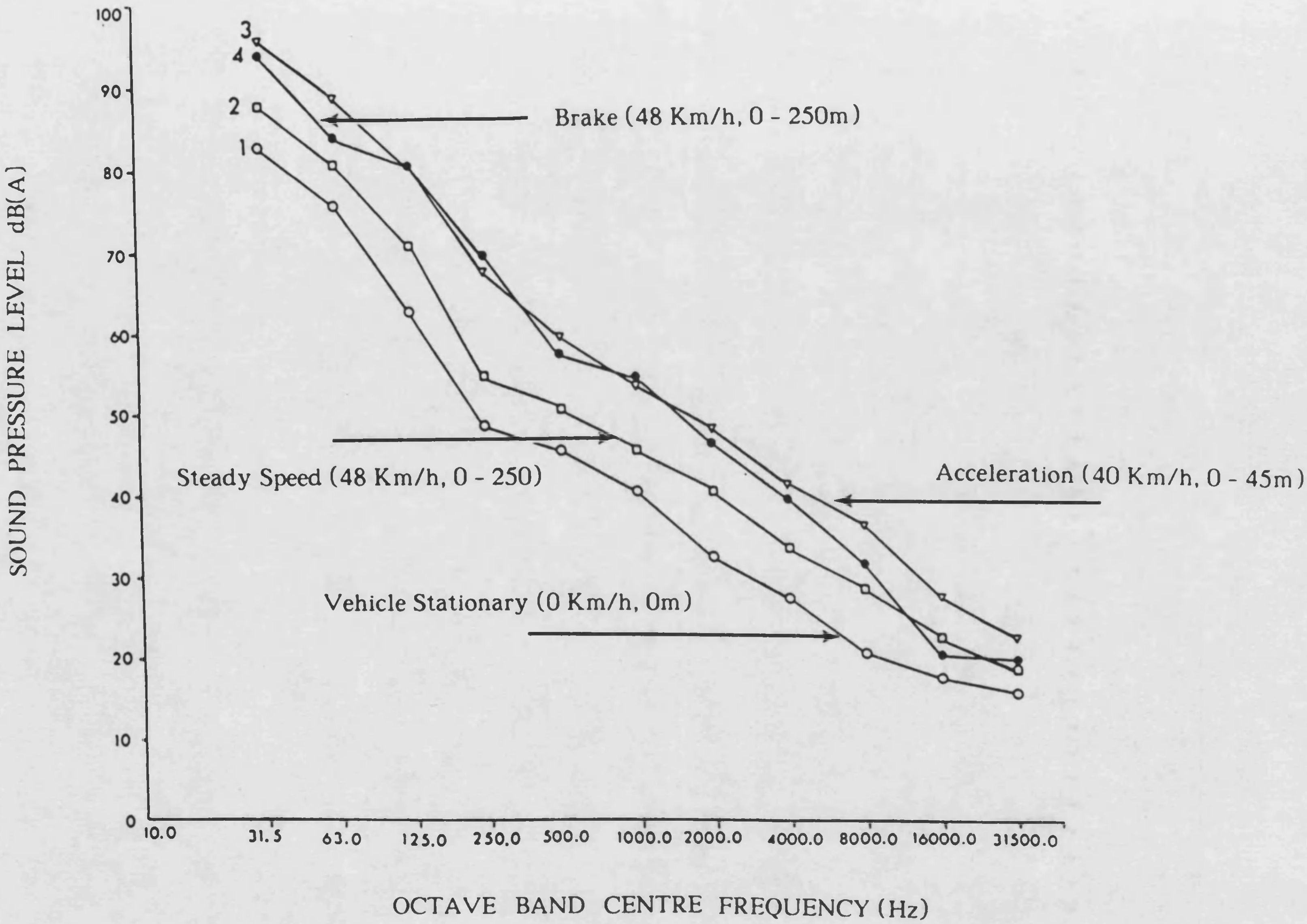


Fig 5.6 Characteristics of noise spectra inside the passenger cars

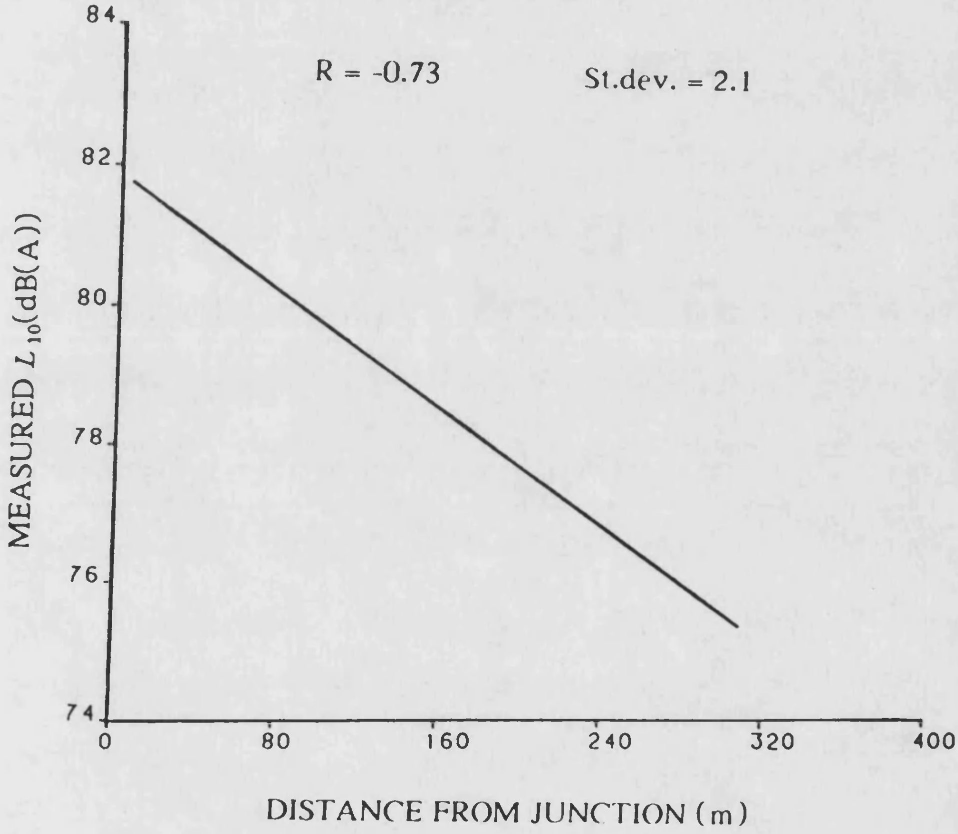


Fig 5.7 Relationship between noise level and distance from junction
(Simultaneous measurements at 10 Locations - see Table 5.1)

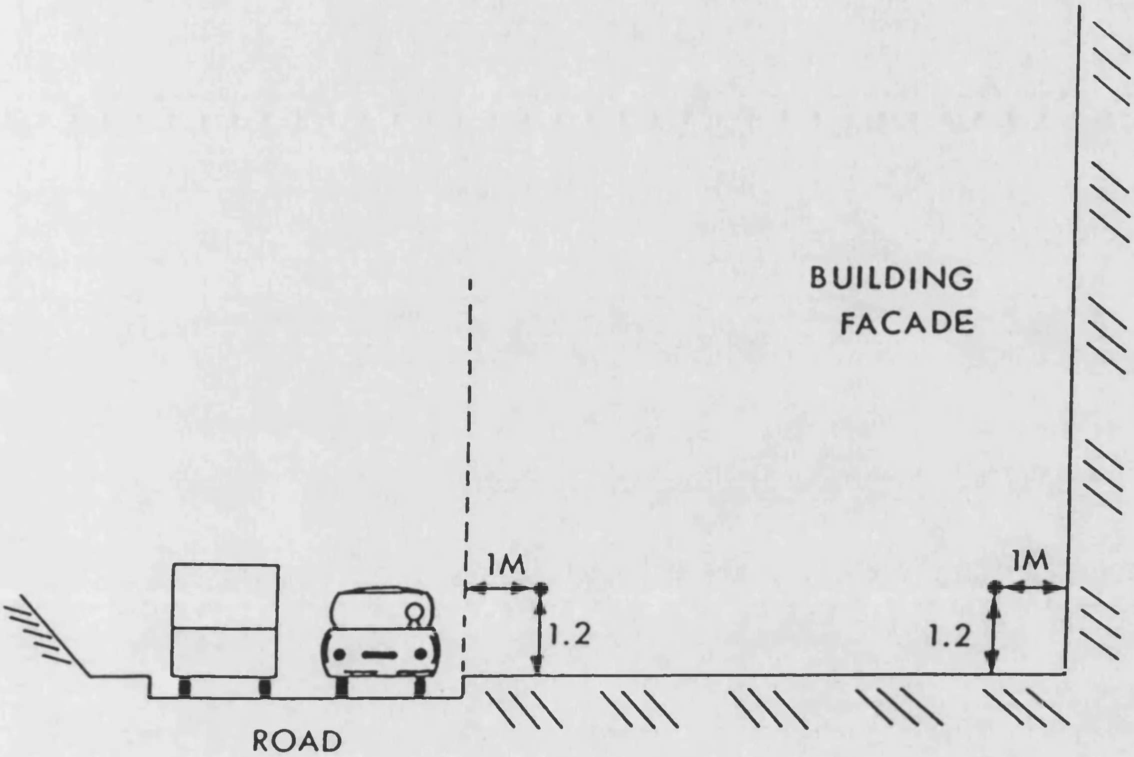


Fig 5.8 Location of simultaneous measurements of noise level at the kerbside and building facade (See Table 5.2).

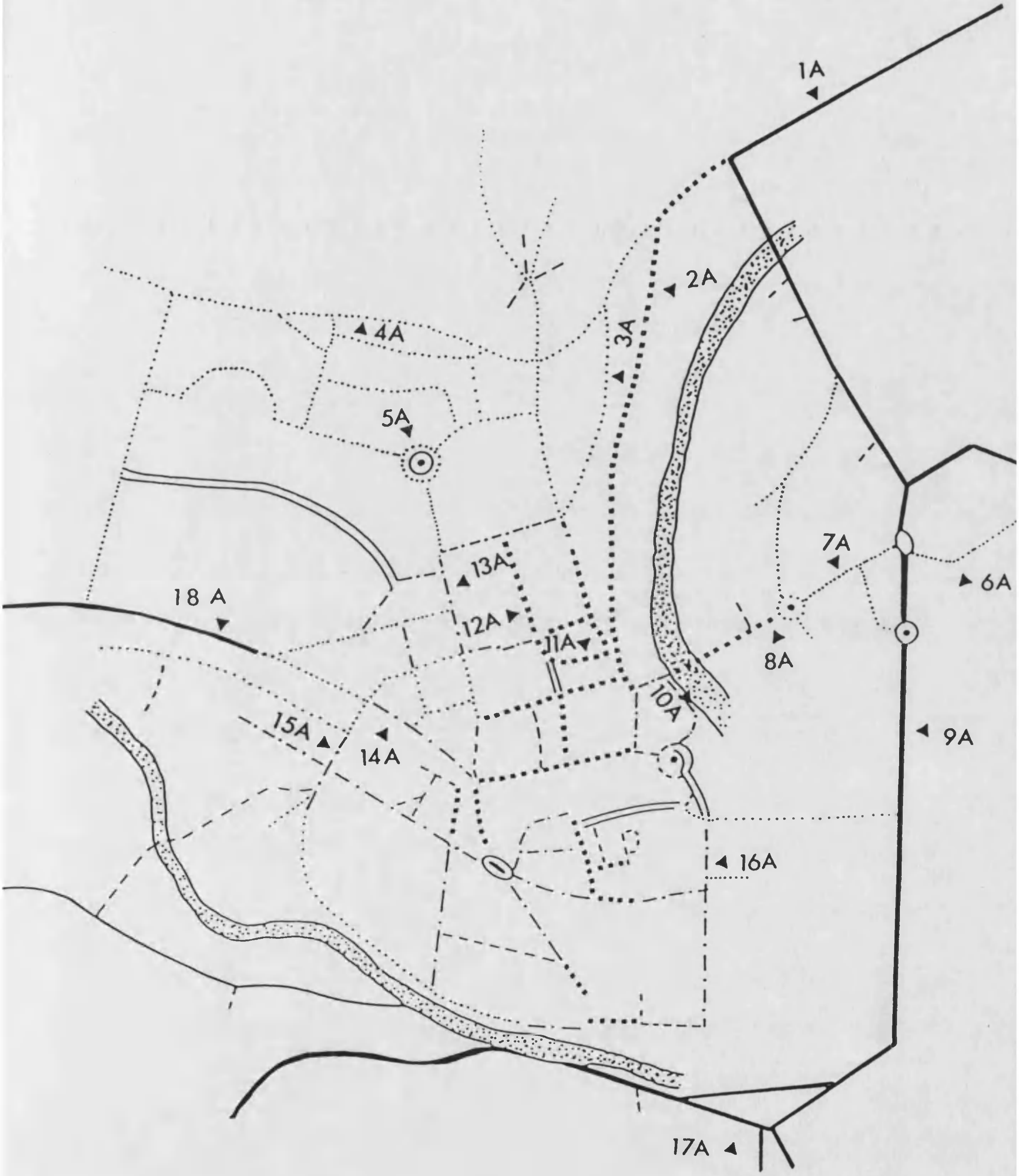


Figure 5.9 Distribution of 18 measured sites (18 hour survey, 6.00-24.00)

4 sites - urban main road area

5 sites - office area

5 sites - residential area

4 sites - shopping area

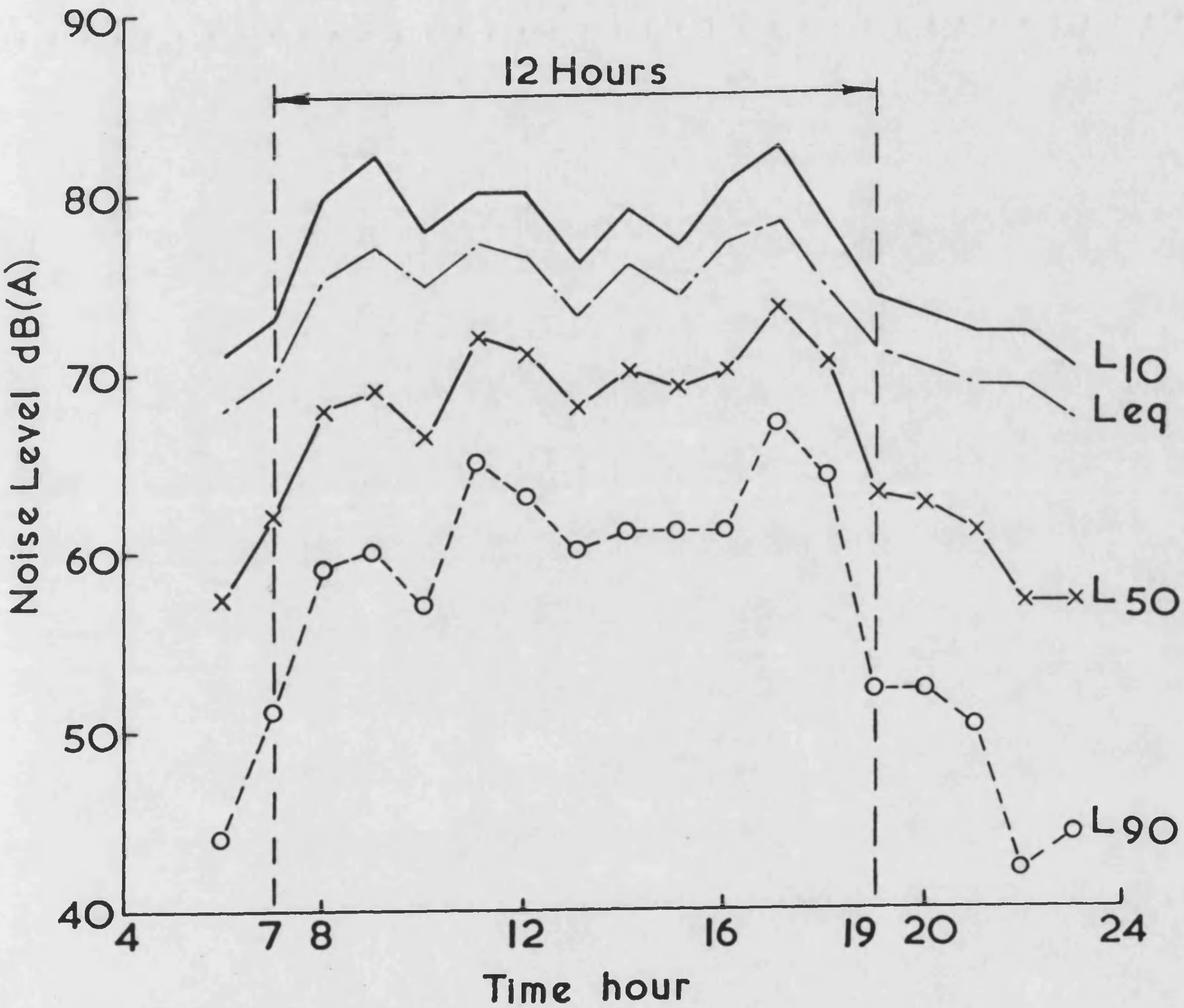


Figure 5.10 The hourly variations in noise level values of L_{10}, L_{50}, L_{90} and L_{eq} at site no. 9A, a typical main route area, Pulteney Road (Heavy traffic condition)

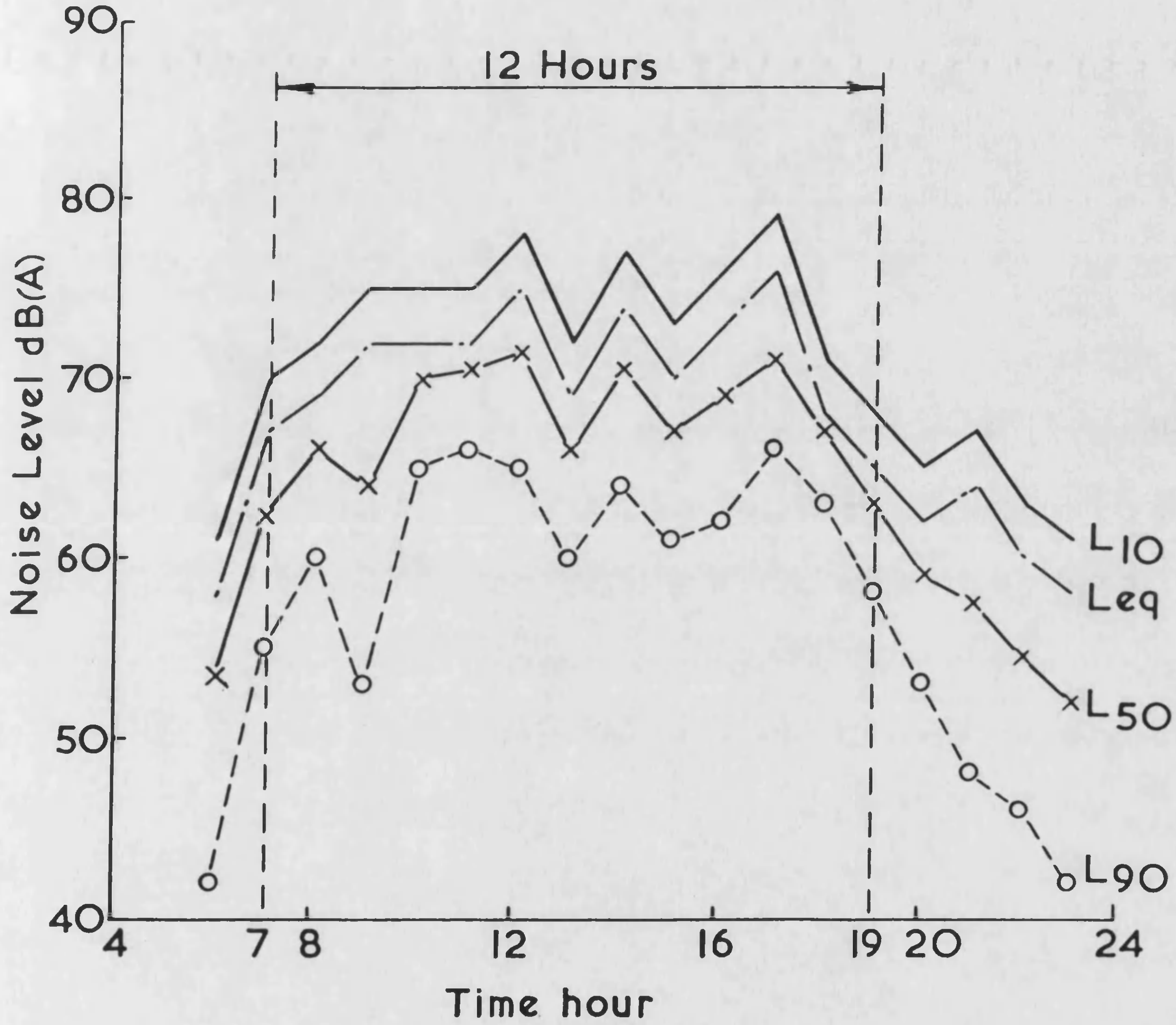


Fig 5.11 The hourly variations in noise level values of L_{10}, L_{50}, L_{90} and L_{eq} at site no. 12A, a typical shopping area. Milsom Street (medium traffic condition)

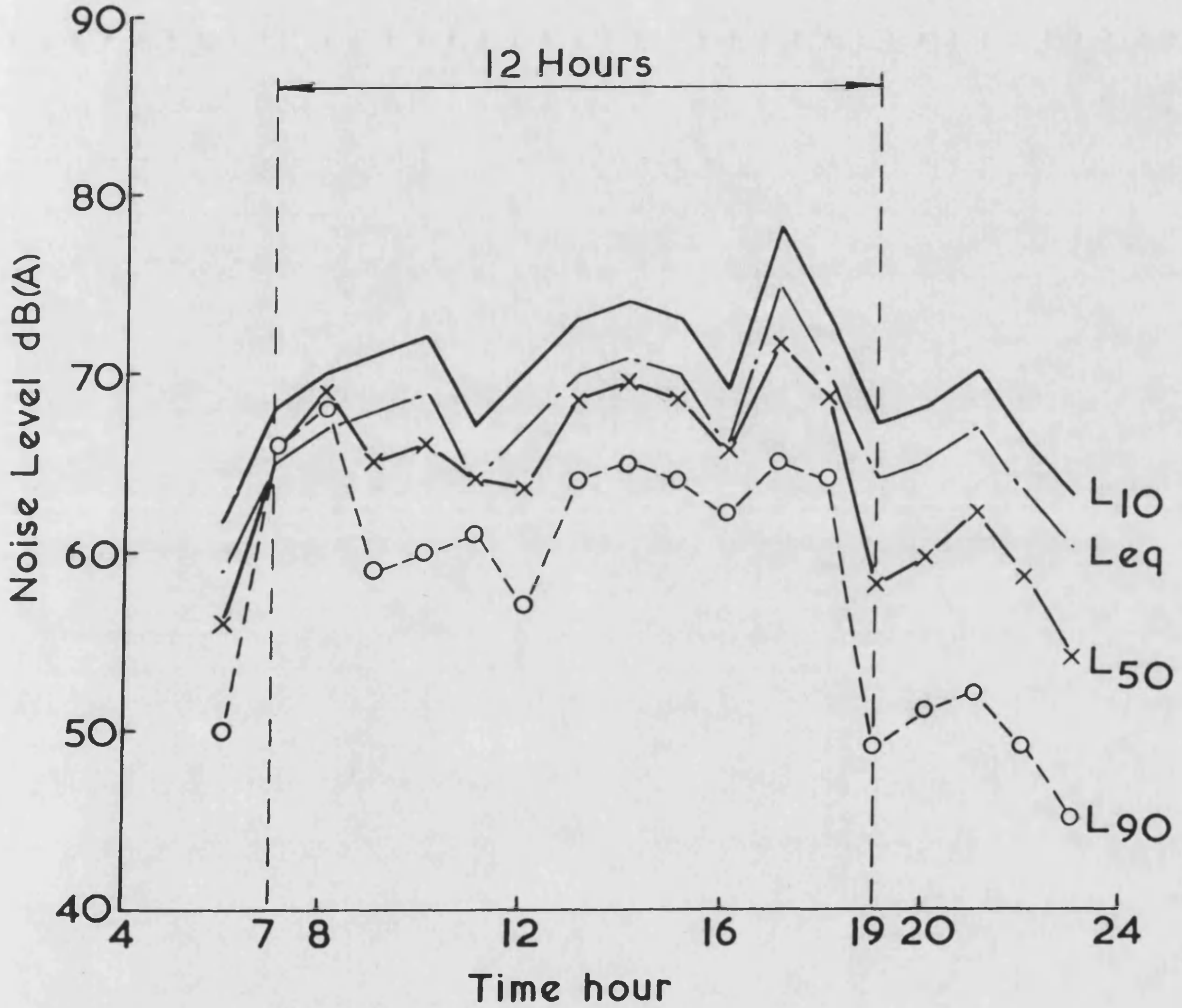
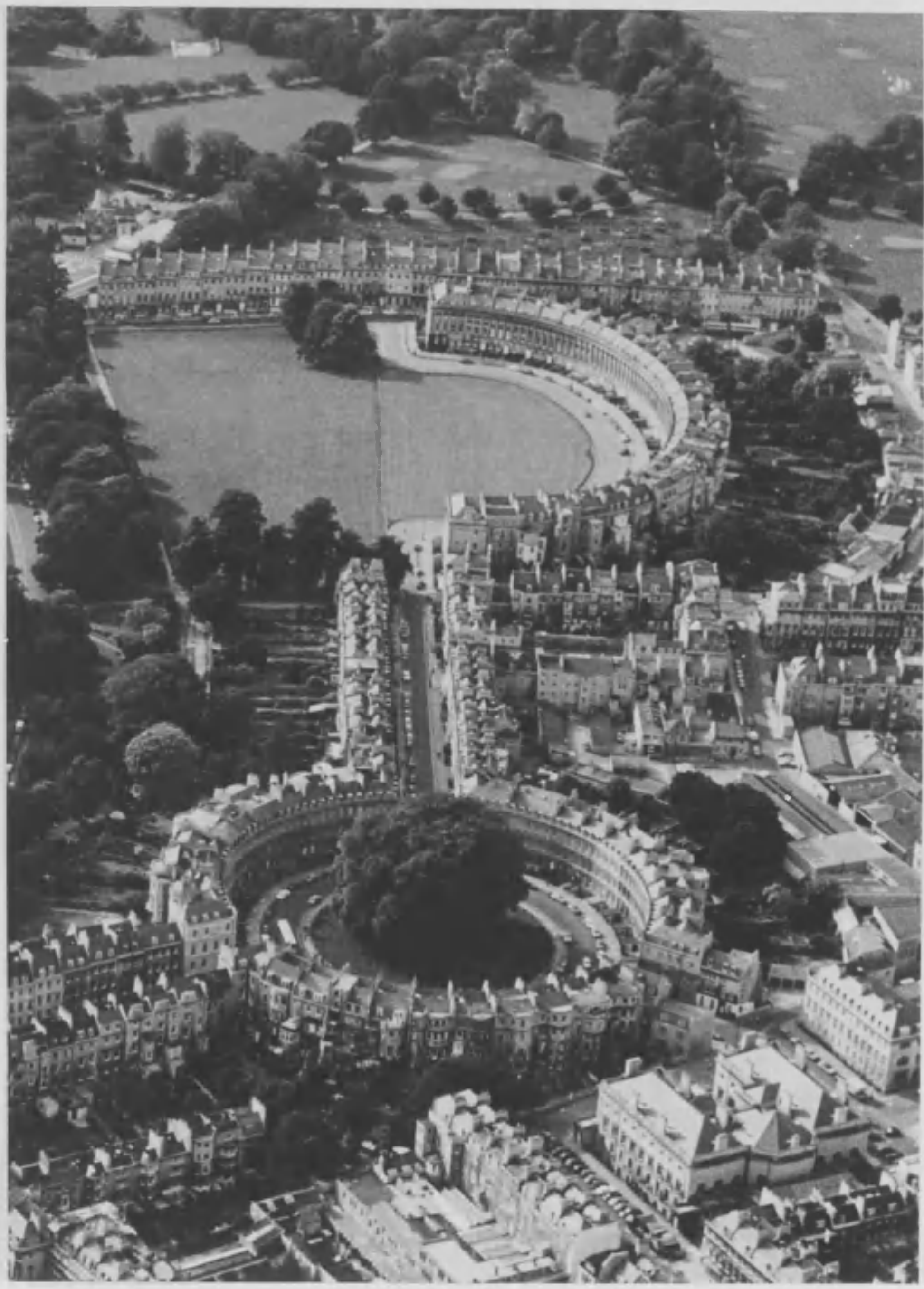


Fig 5.12 The hourly variations in noise level values of L_{10}, L_{50}, L_{90} and L_{eq} at site no. 5A, a typical residential area, The Circus (light traffic condition)



5A

PLATE 1 THE CIRCUS AND ROYAL CRESCENT

Part of architectural character of Bath. Typical residential area (site 5A), carrying light traffic conditions

PLATE 2 RIVER AVON

River Avon, and Greenhill provide for the planners the difficult task of developing satisfactory road network

PLATE 3 LONDON ROAD

Traffic light intersection - Node No. 1. Typical main route, carrying heavy traffic conditions

35

PLATE 4 BATHWICK ROUNDABOUT

Roundabout - Node No. 5. Typical heavy traffic conditions (site No. 35)

12A

PLATE 5 MILSOM STREET

Conflict between pedestrians and vehicles arising in typical shopping area. (site No. 12A)

107

PLATE 6   GREAT PULTENEY STREET

Typical residential area (site No. 107) buildings' facades are on both sides. Visual intrusion arising from parking vehicles.

114

PLATE 7 GEORGE STREET

Typical office area in the heart of the City. Heavily loaded with traffic which forms part of the A4 route (site No. 114)

70

PLATE 8 BATH BUS STATION

The Public Transport operations and National Express Coach Services depart from the City centre (priority junction - Node No. 9), site No. 70

PLATE 9 BATH PEDESTRIAN PRECINCTS

The central pedestrian precincts are entirely reserved for walking people, shopping and for "sitting about and enjoying Bath".

Above: NORTHUMBERLAND PLACE

Below: WEST FRONT OF ABBEY CHURCH

PLATE 10 TYPICAL SITE RECORDING

Sound level meter mounted on tripod and connected to portable tape recorder. Calibration signal to check the stability of recording (site No. 8B)

24

PLATE 11 DIGITAL RADAR SYSTEM

Vehicle speed was measured by a universal Muniquip digital radar system (site No. 24)

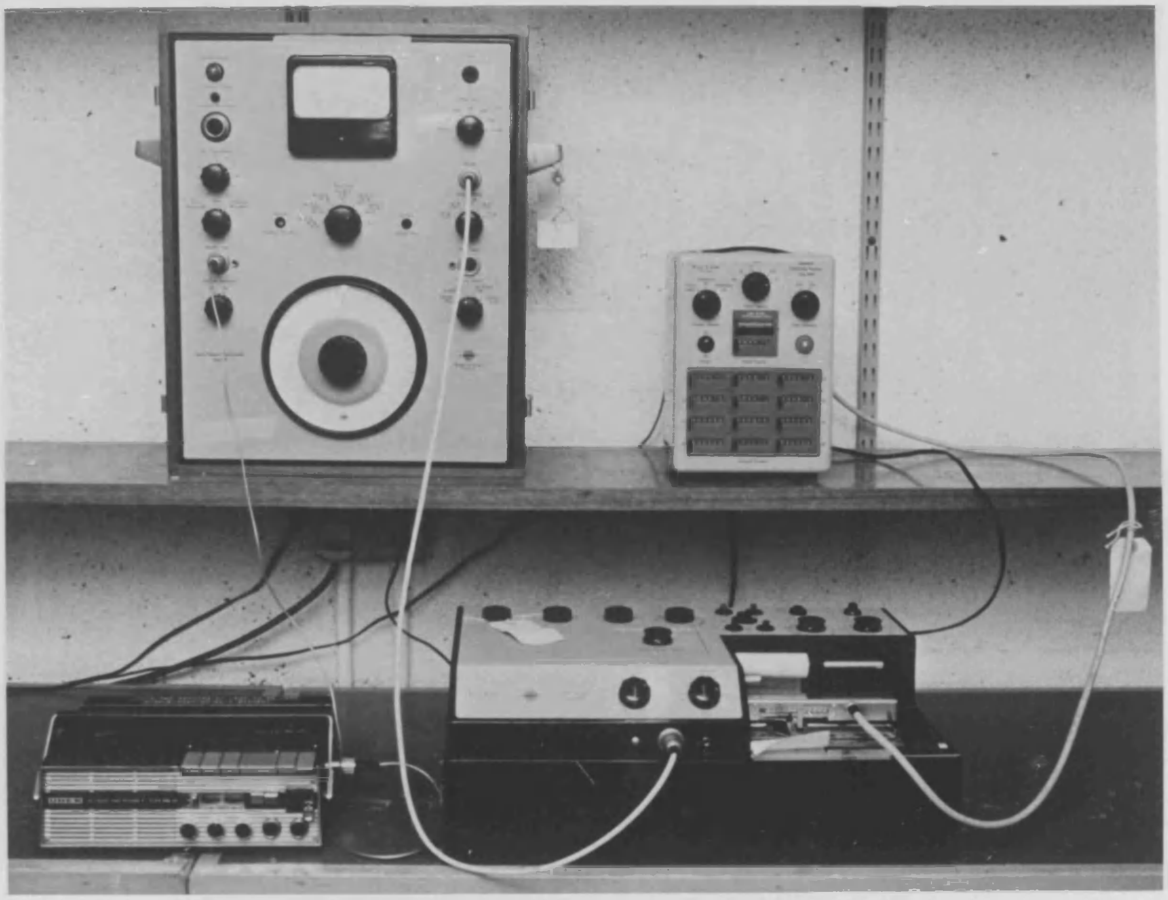


PLATE 12 EQUIPMENT USED FOR ANALYSIS OF ROAD TRAFFIC NOISE

CHAPTER SIX

AN INVESTIGATION OF THE VARIABLES ASSOCIATED WITH ROAD TRAFFIC NOISE UNDER NON-FREE FLOWING TRAFFIC CONDITIONS

6.1 INTRODUCTION

The physical variables associated with the flow of traffic in built-up environments have a direct effect on the amount of traffic noise a person hears (Chapter 3). These are incorporated into the design of roads and buildings and Land Use planning. But, the current literature gives little indication of how these variables might affect the level of noise when they act as individuals or as a group. Besides, some of them have not been well studied due to the complexity of the situation and the large number of contributed features. For these reasons it was decided that this study should cover a wide range of variables which play an essential part in the identification of the urban and suburban environments.

The objective of this chapter is to assess the common variables which influence the structure of noise and the manner in which the situation might be modelled. The chapter involves the following main subjects :

(1) Computer processing and procedure on sites.
(2) Investigation of the character of each considered independent variable and its effect on the level of noise. This includes traffic flow, composition and speed; road width; junctions and building facades.
(3) Investigation of the traffic noise structure associated with the combined variables in the vicinity of roundabouts, intersections controlled by traffic lights and priority junctions.

6.2 COMPUTER PROCESSING

This section deals with the imitation of a real situation by different forms of prediction models. The basic aim is to model the interaction of the variables to identify those design components that will provide for the most efficient model, to enable engineers to forecast operation on a system prior to its construction.

The following subsections will consider the ways in which the variables of interest (Section 5.9) can be included in a prediction models (This chapter discusses the individual relationships while Chapter 7 deals with the combined noise level functions).

6.2.1 Regression analysis theory

Every day people make decisions that are based upon predictions of future events. To make these forecasts, they rely upon the relationships between what is already known and what is to be estimated (intuitive and calculated). If decision-makers can determine how the known is related to the future event, they can aid the decision-making process considerably. The objective of 'regression analysis' is to determine this kind of relationship between variables (Berenson and Levine, 1983).

The term 'regression analysis' comes from studies carried out by the English statistician Sir Francis Galton in 1877. Usually, the application of this method leads to the establishment of an equation which can be used to estimate the unknown value of one variable 'dependent' based on the known value of the other 'independent'. The statistical process by which two variables are considered is called 'simple regression analysis'.

The extension of simple regression to take account of more than one independent variable is called 'multiple regression analysis'. It is the appropriate technique when the investigation of the effect on the dependent term of several independent variables is required simultaneously. Correlation analysis then shows how well the estimated equation actually describes the relationship. The strength of a relationship between the variables is usually measured by the coefficient of correlation whose values range from -1 for perfect negative correlation up to +1 for perfect positive correlation (Berenson and Levine, 1983). With the advent of computers there has been a marked reduction in the amount of effort, expense and time required to apply the multiple regression analysis method.

In connection with road traffic noise, researchers have aimed to develop a model that would predict noise levels associated with road and traffic parameters as described in Chapter 4. The convenient step was to collect and examine field data that would enable a prediction model to be constructed. Thus, the purpose of regression analysis in this study was to determine the relationship between noise levels and each variable of interest, as well as with all the combined variables, in order to build the prediction tools.

6.2.2. MINITAB computing system

The MINITAB is a statistical computing system containing a number of subroutines which can be used to perform regression analysis. It is a general purpose system, useful for plotting, as well as for regression analysis. The system consists of a worksheet of rows and columns in which data is stored. Usually, the output is rich in regression terms. Of these, regression equation, residuals (E), coefficients, correlation coefficient (R), standard deviation (σ) and t-ratio are common examples (Ryan, Joiner and Ryan, 1976).

It was decided to use MINITAB to perform a regression analysis during the process of this study.

6.2.3. NFNOS Computer program

NFNOS is a computer program written by the author to determine the predicted noise level values, in terms of considered variables. It utilises regression analysis method and the MINITAB computing system. The program deals with the reading of input data files and the output of results, according to required statements. Usually the input data files contain the site reference, the total number of measurements and the variables of each location. See Figure 7.5 and Appendix B for a typical output report by the NFNOS program.

Using the NFNOS program, the values of measured noise levels were examined against each variable, and prediction formulas were derived. Prediction models relating noise levels to all the combined variables in connection with each of the three categories of considered junctions were also established (The next chapter involves development of overall models utilise this program).

The main advantages of using regression analysis and MINITAB to determine the output of this research are:

(1) MINITAB provides a high level of error checking techniques.

(2) MINITAB also automatically introduces additional necessary data, e.g. the analysis of variance.

(3) Most of the current prediction models in the field of traffic noise (Chapter 4) are based on regression analysis theory. Thus it is worthwhile to establish links between this study and previous work.

(4) Regression analysis theory has been in public application in transportation engineering for many years.

(5) The regression method has been found to be the most convenient way of developing prediction techniques adapted from true data, in fields where there are many unanswered questions, as is the case in noise from non-steady flowing traffic.

6.3 PROCEDURE ON SITES

172 urban sites were selected to give a wide range of variables. These were as follows: 49 sites were chosen at various distances from roundabouts. 95 sites were selected at different distances from traffic light intersections and 28 sites were selected at various distances from priority junctions, Table 6.1 describes those sites.

Land use	No. of sites	Total
Residential	30	172
Office	42	
Shopping	17	
Open Space	5	
Urban Main Route	78	
No. of intersections with traffic lights	=20	39
No. of roundabouts	= 4	
No. of priority junctions	=15	

Table 6.1 Description of 172 measured urban sites

Sites were required which would be typical of non-free flowing urban traffic. They were selected with roughly similar types of layout characteristics. Building facades were continuous on both sides. The distance between kerb and receiver was one metre with a microphone height of 1.2 meters (see Section 5.6). Thirty-minute recordings were made hourly between 07.00 and 19.00 hours. The measurements were then analysed to provide L_{10}, L_{50}, L_{90} and L_{eq} dB(A) values. Variables of interest were recorded simultaneously.

Wind, fog and extraneous noise sources (e.g. railway) were absent. It was decided to measure the noise levels alongside accelerating and decelerating streams of traffic next to a node, and at appropriate distances away, until cruising speed was achieved by the vehicles.

The equipment (see section 5.6) used took up as little space as possible, particularly in busy shopping and office areas, where the movement of pedestrians might have influenced the measuring system. Some readings were omitted where abnormal interference was apparent, e.g. when pedestrians commented or asked questions in a raised voice near the sound level meter.

Parking was prohibited at all of the sites measured. There were no sites near bus stops, construction or maintenance works. Fig. 6.1 illustrate the distribution of 172 measured sites.

Noise from non-free flowing traffic is a complex phenomenon, as mentioned earlier , due to the presence of a large number of contributed variables and the fact that noise levels of various vehicle classes vary from one section of road to another since the vehicles are frequently accelerating, decelerating or manoevering. Thus, the variables which affect the noise levels were recorded simultaneously at each site. Of these, traffic flow, composition and speed, acceleration, road junctions and width and location of buildings will be considered in more detail during the forthcoming sections. Table 6.2 shows the characteristics of urban variables.

Variables	Range	Unit
Light Vehicles (L)	260-2532	v/h
Medium Vehicles (M)	6-474	v/h
Heavy Vehicles (H)	0-99	v/h
Traffic flow (Q)	260-2730	v/h
Percentage of heavy & medium vehicles (P)	0-20	%
Speed(V)	10-48	km/h
Road width (W)	6-18	m
Distance from junctions (J)	4-327	m
Distance of nearside building facade (N)	0.5-24	m
Distance of farside building facade (F)	9.35-37.5	m

Table 6.2 Characteristics of Urban Variables

6.4 TRAFFIC FLOW (Q)

Traffic flow is the number of vehicles passing a specific point for a stated period of time. There are many purposes for which flow measurements are required, such as accident studies, improvements to and design of roads, junctions studies (e.g. reduction of delay), control measures (e.g. 'No Waiting' restrictions), growth factors (e.g. expected growth of traffic), cost-benefit analysis and studies of the environmental effects of the operation of the transport system (see Section 3.3.2.1).

Under non-free flowing conditions traffic flow has a complex nature because of land use and variability through day and night. Thus, noise from stop-go traffic is the significant aspect in an urban area.

For freely and non-freely flowing traffic, the noise level has been found to be related to the logarithm of traffic flow, $\log_{10}Q$, rather than simply to traffic flow (Q). This form of relationship was also found to be true in this study. Comparison between the results shows a remarkable increase in correlation coefficient when going from a linear to a logarithmic relationship between L_{10} dB(A) and traffic flow. A similar effect will be noticed in the next investigations as the majority of the variables display a logarithmic relationship with noise levels. A traffic noise survey at 172 sites (2064 thirty-minute samples) showed significant correlation between L_{10} dB(A) and Log_{10} Q (v/h), R=0.70 (The critical value of R=0.138 at the 0.05 level of significance). The straight line can be seen to fit the experimental results quite well, Figure 6.2. The following regression equation was found to fit the data best:

$$L_{10} = 51.1 + 8.61 \log_{10}Q \qquad \text{... (6.1)}$$

where:

R = 0.70 (significant)

St. Dev. = 2.55

The graph indicates that the noise level increases as traffic flow increases. The increase is 2.6 dB(A) when the number of vehicles per hour is doubled. A 95% confidence interval estimate was employed to check the significant of the model. The aim was to set up the 95% confidence interval estimate of the true slope of the relationship and to determine whether the null hypothesis value is included in the interval. The following formula was used (Berenson and Levine, 1983): [$(b_1 \pm tS_{b_1})$, b_1 is the coefficient of the predictor, S_{b_1} is the standard deviation of the coefficient and t is the critical value of t-distribution on appropriate degree of freedom (df)]. The true slope is estimated with 95% confidence to be between +1.1 and +0.80 (The null hypothesis has been rejected). Had the interval included zero, no relationship would have been determined. So the model is significant. Figure 6.2 also shows that there is a significant relationship. The scattering of the data around the regression line shows only a few points out of the confidence limits. Table 6.4 shows the correlation coefficients of noise indices and the considered independent variables.

A test of a null hypothesis was also used to check the significance of the model. By comparing:

$$\text{the Variance Ratio (VR)} = \frac{Meansquare, MS, (regression)}{Meansquare, MS, (residual)}$$

with the critical value of f-distribution (f) on appropriate df. The VR = 94.2. The $f\ (1{,}170)_{0.1\%} = < 11.4$ (1 is the df of regression and 170 is the df of residual, at upper 0.1% tail area of the f-distribution). So the model is significant since VR value is much higher than the value of f. Table 6.5 shows the test of significance of the considered independent variable models.

An interesting comparison was found between the above equation and the former work reported by TRRL (Gilbert *et al.*, 1980) and the Department of the Environment (1975). Results for the purposes of comparison were obtained by inputting the actual traffic and road variables into the two former models and comparing the results to the field measurements. Table 6.3 shows the number of sites, correlation coefficient and standard deviation.

Model	Correlation Coefficient	Standard Deviation	Sites
TRRL $L_{10} = 34.2 + 12 \log_{10} Q$	0.64	2.9	172
DOE $L_{10} = 28.1 + 10 \log_{10} Q$	0.59	3.4	172
Bath $L_{10} = 51.1 + 8.61 \log_{10} Q$	0.70	2.55	172

Table 6.3 Comparison of Bath Model (Traffic flow) and Former Methods

The high degree of scatter which is evident from the graphical presentation of the result, in this section and what follows, is to be anticipated due to the wide range of vehicle types, driver behaviour and many other conditions encountered in real situations. It occurs in spite of the statistical significance of the obtained correlation coefficients, because of the large number of the measurements taken. This scatter is also a good indication of the interaction between the variables in built-up areas and of the best way to treat them - as individual factors or as group. Therefore, formulas of various structures were fitted to the data until the best correlation coefficient was obtained and where further treatment would not give a better correlation. Since the aim of this study is to evaluate the characteristics of noise levels, the functional form which best represented these characteristics is considered, in this section and what follows.

6.5 TRAFFIC COMPOSITION (C)

The composition of traffic (Section 3.3.2.2) affects the capacity of urban roads and junctions to varying degrees. For example, in design matters a heavy goods vehicle is rated as equivalent to two cars on an urban road, and at signalised intersections as equivalent to 1.75 cars (Ministry of Transport, 1966). Thus, study of traffic composition is necessary for design purposes.

In this study vehicles have been classified as light, medium or heavy. The classification has been made primarily on the basis suggested by Nelson and Piner (1977) which was discussed earlier. Differences in noise output between various classes of vehicles have been reported. However, in non-freely flowing traffic there is still a need to investigate this difference especially under normal traffic operations, for the purposes of noise control.

6.5.1. Light vehicles (L)

The values of L_{10} dB(A) obtained at 172 sites were examined against the number of light vehicles, Fig. 6.3. The best final equation was:

$$L_{10} = 52.2 + 8.39 \log_{10} L \qquad \dots (6.2)$$

where:

R = 0.567 (significant)

St. Dev. = 2.62

It is clear from Fig. 6.3 that doubling the number of vehicles per hour increases the average noise level L_{10} by 2.5 dB(A).

6.5.2. Medium vehicles (M)

Figure 6.4 shows the values of L_{10} against the number of medium vehicles.

There is a positive correlation, and the best relation was:

$$L_{10} = 67.4 + 5.73 \log_{10}M \qquad \text{... (6.3)}$$

where:

R = 0.64 (significant)

St. Dev. = 2.45

6.5.3. Heavy vehicles (H)

Figure 6.5 shows the positive correlation between L_{10} and the number of heavy goods vehicles. The straight line can be seen to fit the result. The best final regression formula was:

$$L_{10} = 73.9 + 3.55 \log_{10}H \qquad \text{... (6.4)}$$

where:

R = 0.50 (significant)

St. Dev. = 2.93

6.5.4. Overall relationship

Urban traffic noise is produced by a mix of vehicles of different specifications moving under changeable conditions.

The best relationship (172 sites) between urban noise levels and traffic composition was:

$$L_{10} = 51.4 + 8.16 \log_{10}(L + 6M + 10H) \qquad \text{... (6.5)}$$

where:

R = 0.80 (significant)

St. Dev. = 2.4

The above formula shows that there is a straightforward interrelation and quite significant correlation coefficient (see also Tables 6.4 & 6.5). This is also clear from Figure 6.6.

The selective coefficients 6 and 10 (in Equation 6.5 above) were based on evaluation associated with various categories of vehicles. Noise levels were measured in sites where the traffic structure allowed vehicle noise to be selectively measured, especially during the weekend. The chosen sites were at Bath University campus, London Road, George Street and High Street.

The study showed that the proportion of medium and heavy vehicles in the traffic flow influenced the noise levels. The greater the percentage the greater the noise. Noise levels are also affected to a greater extent by the proportion of heavy vehicles than by medium sized vehicles.

The above relation (Eq. 6.5) appears to be more accurate than the traffic flow model(Eq. 6.1). Thus, this result agrees with the fact that in urban situations traffic composition is a significant factor, because the acceleration and maneuver of vehicles have a marked effect on the level of noise at low speed, unlike at the highest speed (see Chapter 2). Above a speed limit of 48 km/h most vehicles are in top gear. So the emitted noise maintains a more or less steady level. Below a speed of 48 km/h speed, gear changing, vehicle type and presence of junctions have obvious effects on the level of noise.

6.5.5. Percentage of medium and heavy vehicles (P)

The correlation coefficient between the percentage of heavy and medium vehicles (P) and L_{10} was R= 0.432 (significant) and the standard deviation was 2.870, Figure 6.7.

The following formula is the most suitable form:

$$L_{10} = 73.8 + 0.3P \quad \text{... (6.6)}$$

No significant increase was observed when the logarithm of P was employed (see Tables 6.4 & 6.5).

6.6 ACCELERATION OF URBAN TRAFFIC

In urban situations, acceleration of vehicles has a great influence on the level of noise. Therefore, this part of the study was initiated to examine typical urban acceleration associated with traffic noise.

The results indicated that the level of noise decreases with the distance from various junctions. The major levels of noise are generated by an accelerating stream of traffic, from different types of junctions and under different traffic conditions.

The highest noise level was 20-50m upstream of the junctions, then the level of noise began to fall away up to 250m when the vehicle reached its cruising speed (depending on the link length). Figure 6.8 shows a typical variation of acceleration noise associated with signalised intersections, roundabout, and priority junctions. It is based on the measurements of selected sites at London Road, Pulteney Road, Great Pulteney Street and Julian Road.

6.7 SPEED (V)

A knowledge of mean speed is essential for traffic management schemes, design and economic studies. The mean speed of traffic is almost totally dependent on traffic flow and composition, road width, and position of junctions (see Section 3.3.2.3).

In urban traffic there is a wide variation in noise levels due to frequent gear changes. It was concluded that noise levels decrease as the speed of the vehicles increases, Fig. 6.9. This is unlike free flowing traffic noise where levels increase with the speed of vehicles. The decrease in noise levels depend on the link length.

The best final regression equation from 172 locations, between L_{10} dB(A) and mean traffic speed was:

$$L_{10} = 87.7 - 7.07 \log_{10}V \qquad \text{... (6.7)}$$

where:

R = -0.40 (significant)

St. Dev. = 2.90

The result shows significant correlation between noise level and mean speed. Furthermore, with regard to the level of significance of 0.05, the figure indicates that there is a clear interaction, (see also Tables 6.4 and 6.5).

6.8 DISTANCE FROM ROAD JUNCTION (J)

The control of vehicular traffic at road junctions has been one of the principal areas in traffic engineering, since junctions critically influence the efficiency of the road network (Section 3.3.1.1).

Clear relationships were found between the noise level and the proximity of road junctions (i.e traffic lights, roundabouts and priority junctions). The levels of noise decrease with the distance from junctions. When vehicles accelerate away, high noise levels are generated, which are highest 20-50 m after the junction, then noise levels begin to fall, until a specific distance is reached, depending on the frequency of junctions. This was also found when the speed of traffic was examined as an individual variable. Figure 6.10

illustrates the relationship of L_{10} dB(A) and the distance from junctions.

The best regression equation was:

$$L_{10} = 78.7 - 0.0157J \qquad \text{... (6.8)}$$

where:

R = -0.40 (significant)

St. Dev. = 2.9

J = The distance between measurement point and the relevant junction (m)

Tables 6.4 and 6.5 show the test of significance of the model.

6.9 ROAD WIDTH (W)

The field study showed that noise levels increased where 2-4 lane roads carried medium and heavy traffic. In shopping and residential areas where medium and heavy vehicles are almost non- existent, or where there is one-way light traffic, the level of noise was lower even when the road had the same width and similar facades. No significant correlation was derived between noise levels and road width only, R=-0.143 (see Section 3.3.1.2).

This result indicates that in an urban area there is a close relationship between road width and other variables, and that these combined influence the level of noise more than road width only. Noise levels were found to decrease with increased road width, when the combined variables were used (Sections 6.13 - 6.15 and Chapter 9).

6.10 POSITION OF BUILDING FACADES

In built-up areas, road networks are usually surrounded on both sides by buildings of various use which have an influence on the level of propagated noise due to multiple reflections (Section 3.3.4). The extent to which the noise is reflected depends upon the distance of the building facades from the nearside kerb. In the case of the buildings on the opposite side of the road, the reflected noise depends upon the road width, the distance of the farside facade from the farside kerb & the distance between measurement point and nearside kerb. Also, reflection depends on the height and type of the building and the acoustically absorbent quality of their exterior.

It was decided, therefore to examine the distance of the nearside and farside facades which play a significant part in the reflection of noise, since the building height and type were roughly similar.

The following formulas describe the relationships:

$$L_{10} = 78.8 - 2.65 \log_{10}N \qquad \ldots (6.9)$$

$$L_{10} = 85.3 - 6.48 \log_{10}F \qquad \ldots (6.10)$$

where:

R = -0.224 (significant) & st.dev. = 3.10 (Eq. 6.9)

R = -0.230 (significant) & st.dev. = 3.10 (Eq. 6.10)

N = The distance between nearside facade and measurement point (m).

F = The distance between farside facade and measurement point (m).

Figures 6.11 and 6.12 illustrate the relationships between L_{10} and position of buildings. See also tables 6.4 and 6.5 for the test of significance.

6.11. THE RELATIONSHIP BETWEEN SPEED AND JUNCTION DISTANCE

An urban road network is described as a series of nodes and connecting links (Chapter 3). Therefore, when studying road traffic the interaction of speed and the effect of frequency of junctions are of great importance.

This section has presented the relationship between speed and distance from junctions under different urban conditions. Figure 6.13 shows that the mean speed increases sharply as the distance increases. Most of the speed measurements were taken during the traffic noise survey in Bath. Thirty-minute measurements were made hourly at each site between 7.00 and 19.00 hours, using a digital radar system.

Measurements were made at 172 sites and 39 junctions were studied. A speed restriction of 48 km/h existed at all sites, but the speed measured at some sites, reached 57 km/h. Measurements were taken at different distances from the nearest relevant junction and alongside the accelerating and decelerating streams of traffic.

It was found that the mean speed of vehicles increased until the cruising speed had been reached.

The best new formula was of the form:

$$V = 20.4 + 0.119\,J \qquad \text{... (6.11)}$$

where:

$R = 0.85$ (significant)

st.lev. = 7.6

6.12 RELATIONSHIP BETWEEN NOISE INDICES AND INDEPENDENT VARIABLES

It can be seen from previous sections how L_{10} dB(A), interacts with various individual variables in built-up areas. In order to test the validity of other noise indices, Table 6.4 shows the correlation coefficients of the independent variables and L_{10}, L_{50}, L_{90} and L_{eq}. It is clear that L_{10} is at the top of the list followed by L_{eq}. High correlation was also found between L_{10} and L_{eq}. Table 6.6 illustrates the correlation coefficients between various noise indices.

Therefore, L_{10} and L_{eq} will be employed in what follows, as they best represent the level of noise. L_{50} and L_{90} will be considered also for the purpose of comparison, in spite they gave lower correlations. Other noise indices such as TNI and lnp (Section 4.3) gave even much lower level of interactions with the dependent and independent variables of this study. So they were not included in the investigation.

Variables	Noise levels dB(A)			
	L_{10}	L_{50}	L_{90}	L_{eq}
$\log_{10}Q$	0.70	0.589	0.534	0.60
$\log_{10}L$	0.567	0.548	0.541	0.555
$\log_{10}M$	0.640	0.612	0.542	0.617
$\log_{10}H$	0.50	0.407	0.401	0.403
P	0.432	0.406	0.361	0.413
$\log_{10}V$	-0.40	-0.314	-0.233	-0.390
$\log_{10}W$	-0.143	-0.105	-0.080	-0.156
J	-0.40	-0.336	-0.274	-0.386
$\log_{10}N$	-0.224	-0.170	-0.124	-0.223
$\log_{10}F$	-0.230	-0.170	-0.123	-0.230
$\log_{10}(L+6M+10H)$	0.80	0.590	531	0.638

Table 6.4 Correlation Coefficients of Noise Indices and Independent Variables (R=0.138 at 0.05 level of significance)

Model No.	Independent Variable	f-distribution (0.1%)	VR
6.1	Traffic Flow ($\log_{10}$)	< 11.38	94.2
6.5	Traffic composition ($\log_{10}L+6M+10H$)	< 11.38	127.7
6.6	Percentage of medium and heavy vehicles (P)	< 11.38	39.2
6.7	Traffic Speed ($\log_{10}V$)	< 11.38	32.7
6.8	Junction distance (J)	< 11.38	28.6
6.9	Nearside facade distance ($\log_{10}N$)	< 11.38	11.5
6.9	Farside facade distance ($\log_{10}F$)	< 11.38	11.6

Table 6.5 Test of significant of single independent variable models. (The prediction models, L_{10} dB(A), are significant since f is lower than VR)

	L_{10}	L_{50}	L_{90}	L_{eq}
L_{10}		0.945	0.840	0.989
L_{50}			0.951	0.933
L_{90}				0.831

Table 6.6 Correlation Coefficients between various Noise Indices (dB(A))

In order to identify the degree of interaction between L_{10} and each pair of variables which have close partnership as well as to evaluate the effect of more than one variable on the structure of noise, the following relationships were obtained:

(1) Traffic composition and speed:

$$L_{10} = 61.0 + 9.46 \log_{10}(L+6M+10H) - 9.61 \log_{10}V \qquad \text{... (6.12)}$$

where:

R = 0.85

st. dev. = 1.693

(2) Traffic composition and junction distance:

$$L_{10} = 48.8 + 9.45 \log_{10}(L+6M+10H) - 0.0218\ J \qquad \text{... (6.13)}$$

where:

R = 0.84

st. dev. = 1.750

(3) Traffic composition and distance from nearside facade:

$$L_{10} = 48.5 + 9.84 \log_{10}(L+6M+10H) - 5.40 \log_{10}N \qquad \text{... (6.14)}$$

where:

R = 0.80

st. dev. = 1.962

(4) Traffic flow and percentage of medium and heavy vehicles:

$$L_{10} = 53.0 + 7.48 \log_{10}Q + 0.203 P \qquad \text{... (6.15)}$$

where:

R = 0.66

st. dev. = 2.388

(5) Speed and junction distance:

$$L_{10} = 48.8 - 4.71 \log_{10}V - 0.0075 J \qquad \text{... (6.16)}$$

where:

R = 0.42

st. dev. = 2.886

(6) Traffic flow and speed:

$$L_{10} = 59.5 + 10.7 \log_{10}Q - 10.3 \log_{10}V \qquad \text{... (6.17)}$$

where:

R = 0.83

st. dev. = 1.797

(7) Traffic flow and junction distance:

$$L_{10} = 48.4 + 10.0 \log_{10}Q - 0.0212 J \qquad \text{... (6.18)}$$

where:

R = 0.78

st. dev. = 1.986

(8) Nearside and farside building facades:

$$L_{10} = 83.0 - 1.47 \log_{10}N - 3.96 \log_{10}F \qquad \text{... (6.19)}$$

where:

R = 0.25

st. dev. = 3.083

The above equations indicate that there is an increase in the level of correlation in contrast with the individual items. These relationships are also presented in a three dimensional form in figures 6.14 - 6.21. Curves gained from the figures illustrate L_{10} behaviour. L_{10} increases when Q,C & P increase, while the level decreases as V, F, J and N increase. This conclusion reflects the influence on environmental noise of urban features when they are combined.

6.13 NOISE FROM URBAN TRAFFIC AT ROUNDABOUTS

6.13.1 Introduction

In 1925, the first examples of gyratory layout were constructed in the United Kingdom. Subsequently, rotary intersections were adopted at many major intersections in London and in several of the bypass roads constructed between the two World Wars. Roundabouts are now commonly used in Britain as a simple and safe means of traffic control at junctions. In their basic form they are junction structures where a number of two-way roads join a one-way circular carriageway thus allowing the movement of all traffic between adjoining roads, giving way to the right. Prior to 1966, entering and circulating traffic had equal priority with the result that during heavy traffic demand, entering traffic sometimes impeded traffic leaving the junction and the roundabout would 'lock'. The introduction of the 'giving way to traffic from the right' rule completely removed this operational difficulty making them widely acceptable, and it became possible to contemplate more compact roundabout designs. In 1968, the first mini-roundabout was installed for the public in the UK. This successful trial was quickly followed by others at a number of sites with widely different characteristics. The first double roundabout was installed on public roads in 1970. Since then more complex designs have been tried in which the larger junctions with four or more arms have been split into several three-way roundabouts connected by two-way link roads (Maycock, 1976).

Based on Transport and Road Research Laboratory practice (Maycock, 1976), roundabouts may be considered to fall into two categories: firstly, conventional roundabouts with large central islands and parallel-sided weaving sections, and secondly, offside priority roundabouts with small islands and phased entries.

TRRL studies also show that there are a number of injurious accidents at roundabouts and delay due to geometry of the roundabout ranges from 4 seconds to 15 seconds depending on the diameter, the central island, and on the normal speed for the approach.

There is little information on the structure of urban traffic noise near roundabouts (Section 3.3.1.1). Levels can differ from those due to freely flowing traffic because vehicles are decelerating, accelerating, changing lane, queuing and negotiating the rotary section. Thus, in the vicinity of the roundabout the measured noise level is affected by many factors. This section involves a study of noise levels near various roundabouts under normal urban traffic operations.

6.13.2 Description of sites

Sites were chosen at varying distances from roundabouts with no gradients, dry road surface, no wind and no side-traffic effects. They were typical of non-free flowing traffic. Two of the roundabouts used in the study formed part of Bath's main roads, the other two carried medium traffic conditions only. See figures 6.1 and 6.22.

The structures of the roundabouts studied were as follows:

(1) Bathwick Roundabout: This is at the northerly end of Pulteney Road where it meets Bathwick Hill. The approach roads studied were Pulteney Road and Darlington St. They are straight, and carry two-way traffic. The central island is circular and large. The roundabout forms part of one of Bath's main roads. The measurement positions are along the roads at different distances from the roundabout and 1m from the kerbside. The building facades are on both sides. It is an uncontrolled roundabout, 430m from a signal- controlled junction at Pulteney Road and 200m from the Darlington St. priority junction with Sydney Road.

(2) Mini-Roundabout: This is at the southern end of the London Road where it meets Walcot Street and the Paragon. The approaches studied were the Paragon, London Road and Walcot Street. They carry two-way traffic. The central island is circular and small. The measurements were along the roads at varying distances from the mini-roundabout. Building facades are on both sides. It is an uncontrolled mini- roundabout carrying a heavy traffic load.

(3) Laura Place Roundabout: It is uncontrolled and carries a medium traffic load. It is at the beginning of Argyle Street where it meets Great Pulteney

Street. The approach streets carry two-way traffic. The central island is circular.

(4) Technical College Roundabout: It is uncontrolled with an elliptical central island. It carries a medium traffic load. The approach streets are St. James Parade, James Street West, Monmouth Street and Hot Bath St. which carry one and two way traffic.

6.13.3 Results

49 sites were selected at varying distances from roundabouts. Analysis of noise levels obtained from traffic accelerating from and decelerating towards roundabouts was made.

Clear relationships were found between the noise levels and proximity of roundabouts. For the acceleration and deceleration sides a clear trend towards higher levels closer to the roundabout was found, with this trend more marked for the accelerating stream of traffic. When the vehicles accelerated away high noise levels were generated. Then noise levels began to fall away, when the vehicles reached cruising speed. Table 6.7 shows some measurements at different distances from roundabouts. It was concluded that the noise produced by vehicles on the approach roads to the roundabouts was largely dominated by the accelerating stream of traffic. There was no clear character for the noise levels from decelerating traffic. This is probably because the dominance of other factors. Also, because the limited width of road networks, unlike motorways, encourages the dominance of factors which generate a higher level of noise, e.g. the high level of lorry noise at low speed.

As with most urban areas, interaction of motor vehicle noise with related independent variables was evident. It was decided therefore to develop an overall model relating noise levels (L_{10}) to some of the most significant parameters used in planning. The objective was to evaluate the effect of roundabouts on the character and level of noise generated by vehicular traffic operating in a routine way through various urban areas.

Site No.	Land use	Traffic conditions	L_{10} dB(A)	J (m)	V (km/h)	Node No.
41	main road	Heavy	80.4	8	18	5
42	main road	Heavy	76.3	180	37	
43	main road	Heavy	75.7	280	48	
44	main road	Heavy	80.7	9.3	17	5
45	main road	Heavy	75.9	66	35	
78	office	Medium	78.7	5	16	11
81	office	Medium	76	90	32	
94	shopping	Medium	76.7	9	18	15
96	shopping	Medium	73	50	24	

Table 6.7 Typical L_{10} Values at Different Distances from Various Roundabouts, Accelerating Traffic

The best relationship, using multiple regression analysis, was:

$$L_{10} = 54.8 - 6.03 \log_{10}V - 1.80 \log_{10}W - 0.011\ J + 11.4 \log_{10}(L + 6M + 10H) - 6.02 \log_{10}(d\text{-}k) \qquad \text{... (6.20)}$$

where:

$R = 0.978$ ($R=0.27$ at 0.05 level of significance & $R=0.35$ at 0.01 level of significance)

Standard deviation = 0.598

The difference between the measured and predicted values (Residual) = ± 1.7 dB(A) for 95% of the cases

d = the distance between kerb and nearest building facades (m)

k = the distance between measurement points and nearside kerb, i.e 1m

The correlation between noise levels and traffic parameters increased significantly when all the above parameters were applied. Figure 6.23 shows the comparison of measured and predicted values. It was more significant than the correlation coefficient between noise levels and any individual parameter, e.g. distance, See Figures 6.24. However, it appears that there is an obvious effect on noise level in the vicinity of roundabouts and this phenomenon can be modelled accurately. Table 6.9 shows test of significant of junction models.

6.14 NOISE FROM URBAN TRAFFIC IN THE VICINITY OF TRAFFIC LIGHT INTERSECTIONS

6.14.1 Introduction

The first signal was installed in London in 1868 and was of semaphore-arm type with red and green gas lamps for night use. In 1918, the first manually operated three colour light signals were installed in New York and in 1925 manually operated coloured lights were used by the police in London (Salter, 1976).

Nowadays traffic signals are often vehicle-activated and the green period is related to traffic demands. The signal sequence of traffic signals is red, red/amber, green, amber. The amber period is standardised at 3 seconds and the red/amber at two seconds. The latest type of vehicle-activated signals include many facilities such as a minimum green period and a vehicle extension period. Owing to the frequency of junctions in urban areas the linking of signals is often desirable to reduce delays to traffic. The development of traffic control on an urban area basis has led to the development of a number of methods of signal control such as the use of digital computers to provide urban traffic control systems (Mowatt, 1984).

In the control of traffic at intersections the conflict between streams of vehicles is prevented by a separation in time. The procedure by which the streams are separated is known as phasing. In such a situation, vehicles accelerate and decelerate in response to traffic control signals.

This section describes traffic noise measurements carried out along the different approach roads to traffic lights. The aim was to determine how the character and level of noise are affected by the insertion of a traffic light in an urban area under everyday operations.

6.14.2 Sites

95 sites were selected at different distances from the traffic lights. Sites were found to which all the approach roads were straight. The traffic light intersections were chosen to give representative samples of differing traffic conditions.

Figures 6.1 and 6.25 show the distribution of various sites and location of measurement points near the London Road signalised intersection respectively.

Site No.	Land use	Traffic condition	L_{10} dB(A)	J (m)	V (km/h)	Node No.
1	main road	Heavy	83.7	4	15	1
2	main road	Heavy	83.6	11	16	
3	main road	Heavy	84.5	25	27	
4	main road	Heavy	83.5	50	31	
6	main road	Heavy	82.3	79	33	
7	main road	Heavy	79	113	39	
52	main road	Heavy	79.2	11	20	6
55	main road	Heavy	75.7	282	49	
63	office	Medium	81	13	19	7
66	office	Medium	77.9	91	32	

Table 6.8 Typical L_{10} Values at Different Distances from Various Traffic Light Intersections - Accelerating Traffic

It was found that because of the dominant level of noise emitted by the accelerating stream of traffic the separation of noise levels between accelerating and decelerating traffic was difficult, as was found with roundabouts.

The highest noise level was upstream of the traffic lights. Then the noise level began to fluctuate according to the road and traffic conditions.

The final relationships between noise levels and effective variables was:

$$L_{10} = 56.7 - 5.35 \log_{10}V - 4.91 \log_{10}W - 0.0101 J + 11.4 \log_{10}(L + 6M + 10H) - 4.92 \log_{10}(d\text{-}k) \quad \ldots (6.21)$$

where:

R = 0.981 (R=0.19 at 0.05 level of significance and R=0.25 at 0.01 level)

St. Dev. = 0.576

Residual = ± 1.6 dB(A) for 89% of situations.

Figure 6.26 shows the interaction between the measured and predicted values based on the above model. Again, the correlation between noise levels and traffic parameters increased significantly when all the combined parameters were employed rather than individual items. For example, fig. 6.27 shows the relationship between L_{10} values and distance from various signalised intersections. Noise levels are clearly dependent on the proximity of traffic light intersections. The study also suggests that modelling the situation is possible, as in the case of roundabouts. Table 6.9 shows the test of significance.

6.15 NOISE FROM URBAN TRAFFIC AT PRIORITY JUNCTIONS

6.15.1 Introduction

At a priority junction, traffic from the minor road is expected to give way to that on the major road and is controlled by a Give Way sign (Salter, 1976). Full visibility will be needed to the right and left, and the junction should be designed so that vehicles do not have to turn a full lock when turning. Effectively designed junctions should minimise overloading, in order to avoid delays.

6.15.2 Results

For the purpose of this study, 28 sites near priority junctions were measured. It was found that there was a clear tendency towards high noise levels from upstream traffic and in the vicinity of junctions.

The final equation selected was:

$$L_{10} = 55.4 - 5.28\log_{10}V - 5.43\log_{10}W - 0.0143\,J + 12.2\log_{10}(L+6M+10H) - 627\log_{10}(d-k) \quad \text{... (6.22)}$$

where:

R = 0.989 (R=0.36 at 0.05 level & R=0.46 at 0.01 level)

st. dev. = 0.579

Residual = ± 1.8 dB(A)

Fig. 6.28 also shows significant correlation between measured and predicted L_{10} values based on the above equation (see also Table 6.9). There is evidence that priority junctions interrelate with environmental noise levels in built-up situations.

Model No.	Type of Junction	f-distribution (0.1%)	VR
6.20	Roundabout	< 5.13	188.8
6.21	Traffic light Intersection	< 4.76	448.3
6.22	Priority Junction	6.19	208.0

Table 6.9 Test of significant of junction models
(The prediction models, L_{10} in terms of combined independent variables, are significant since VR > f)

6.16 SUMMARY

This chapter has dealt with the factors which affect the extent of noise generation by vehicular traffic in built-up areas when the flow of traffic is non-steady. The selected measurement locations and computer processing have also been described.

L_{10} and Leq have been identified as favourable indices. They were highly affected by a large number of variables which make their level irregular. While Q,C and P were found to maximise the noise levels when they were increased, V,F,J and N had the opposite effect. The regression graphs of these relationships also display clear differences in the degree of correlation. Prediction models relating L_{10} to these factors were developed.

Models for L_{10} as a function of each pair of variables were introduced and represented in a three dimensional form.

The character and level of noise emitted by vehicular traffic as a function of its distance along the approach roads from roundabouts, intersections with traffic lights and priority junctions were examined. Prediction models were established for noise in the vicinity of each junction type associated with the combined variables.

It was found that there is interaction between the related variables. Treating them individually is not an easy task. Furthermore, the correlation coefficient was increased significantly when the combined variables were used.

For the objectives of this study, the best relationship was found between noise levels and the combined variables. It was decided to carry on further analysis (next Chapters) to establish more comprehensive and accurate prediction models in view of the findings of this chapter.

DISTRIBUTION OF 172 MEASURED SITES

Fig.6.1

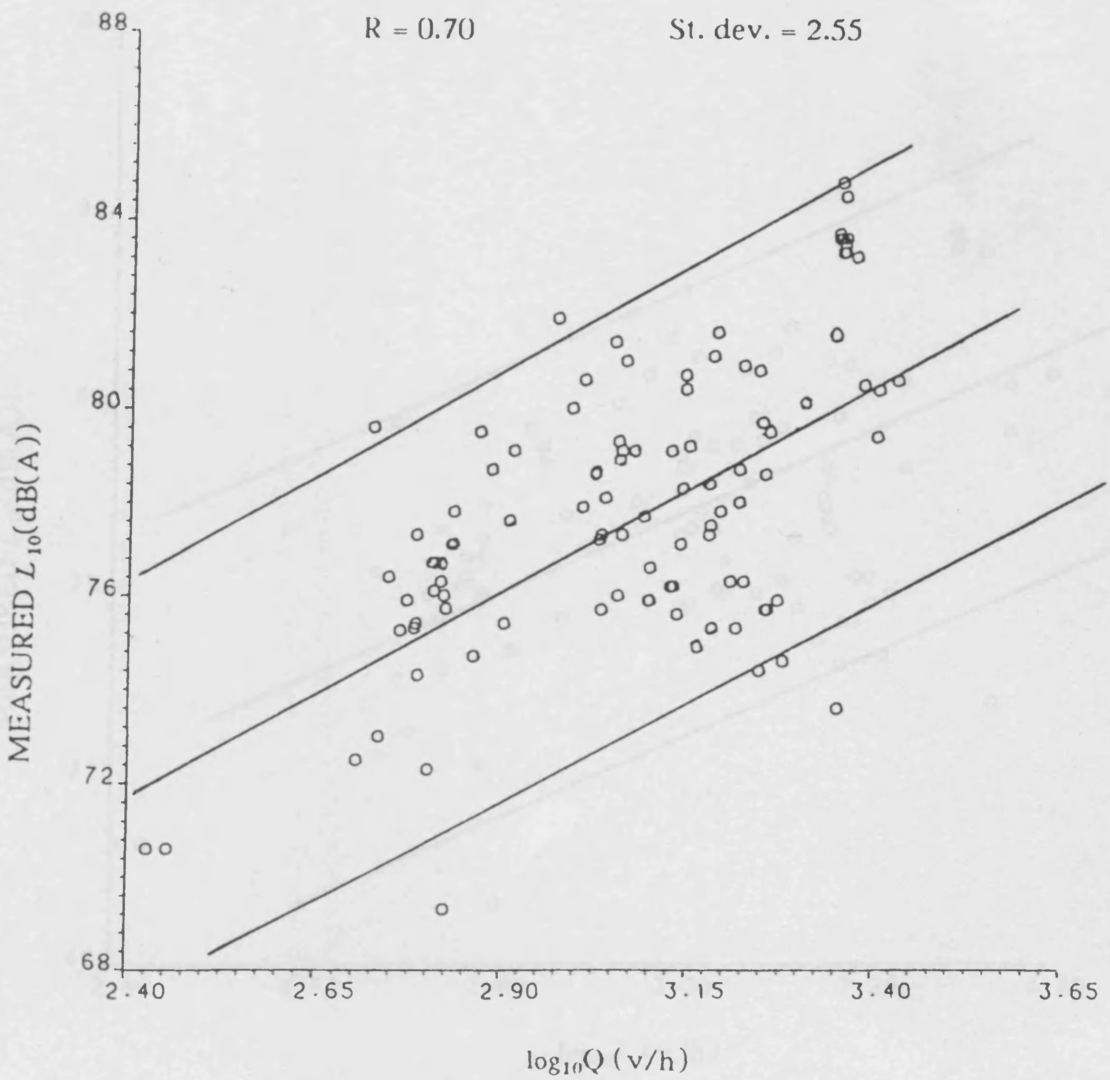


Fig 6.2 Measured L_{10} - traffic flow relationship (Equation 6.1) with 95% confidence limits

R = 0.567 St. dev. = 2.62

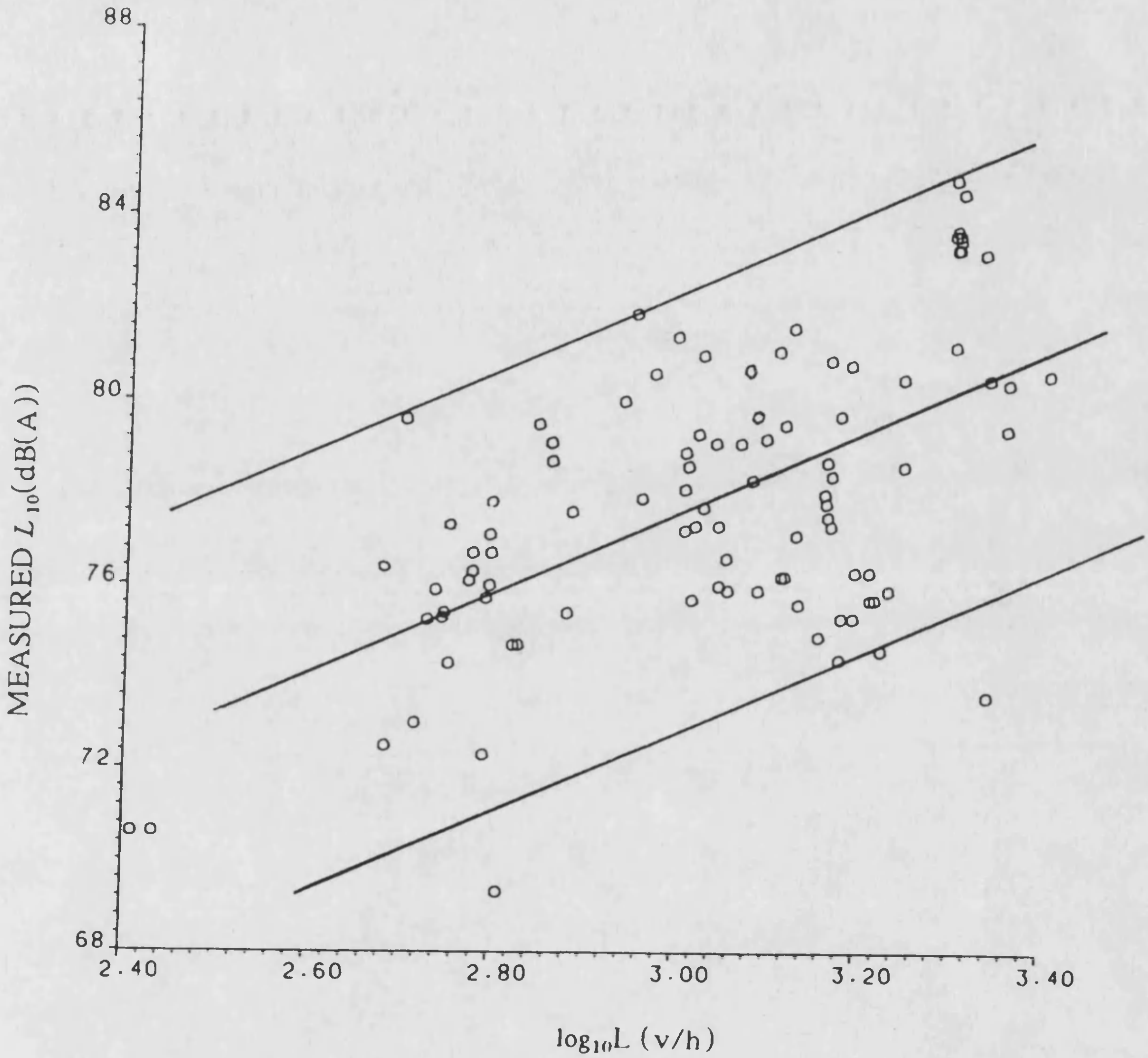


Fig 6.3 Measured L_{10} - light vehicles relationship (Equation 6.2) with 95% confidence limits

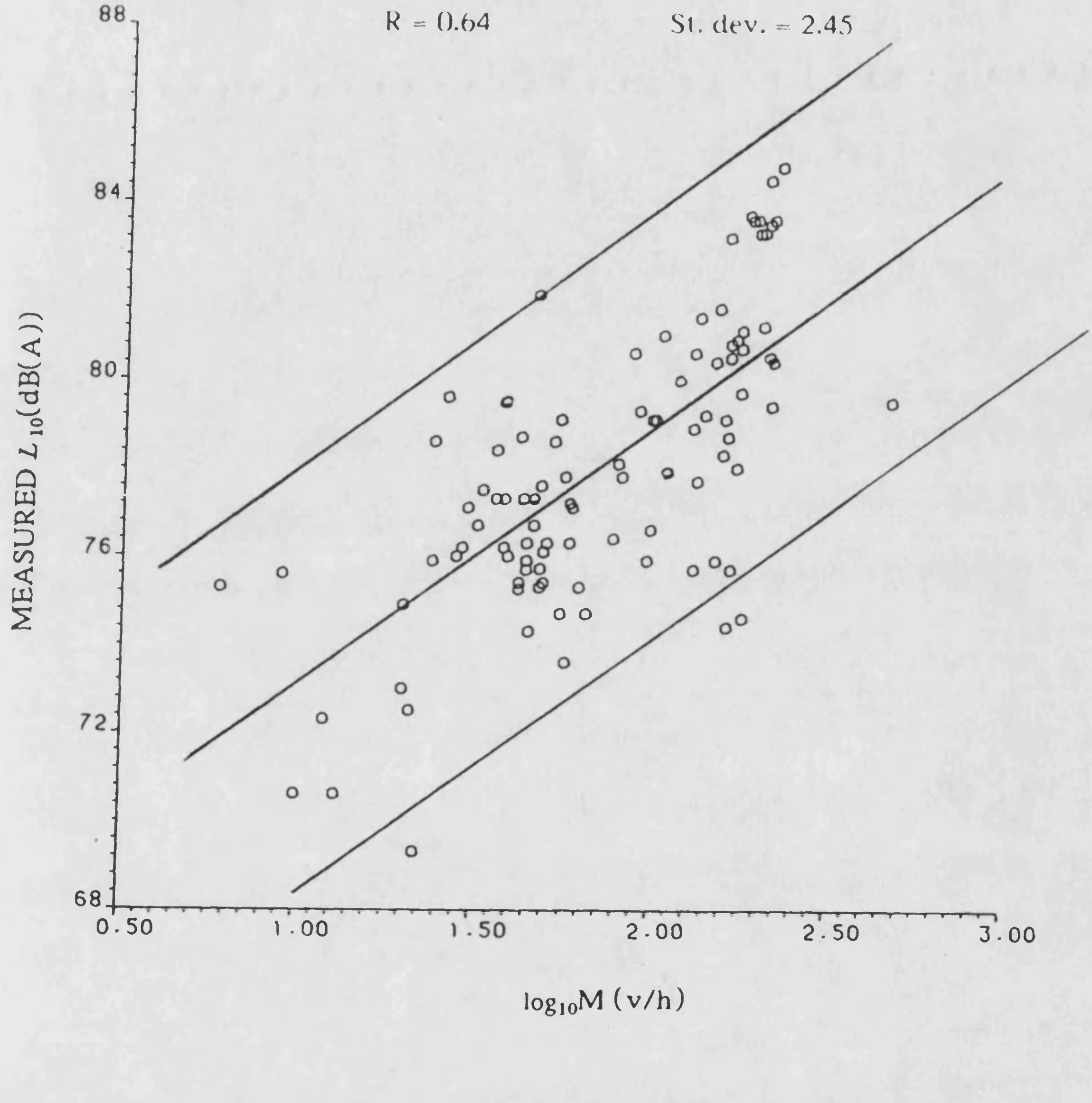


Fig 6.4 Measured L_{10} - medium vehicles relationship (Equation 6.3) with 95% confidence limits

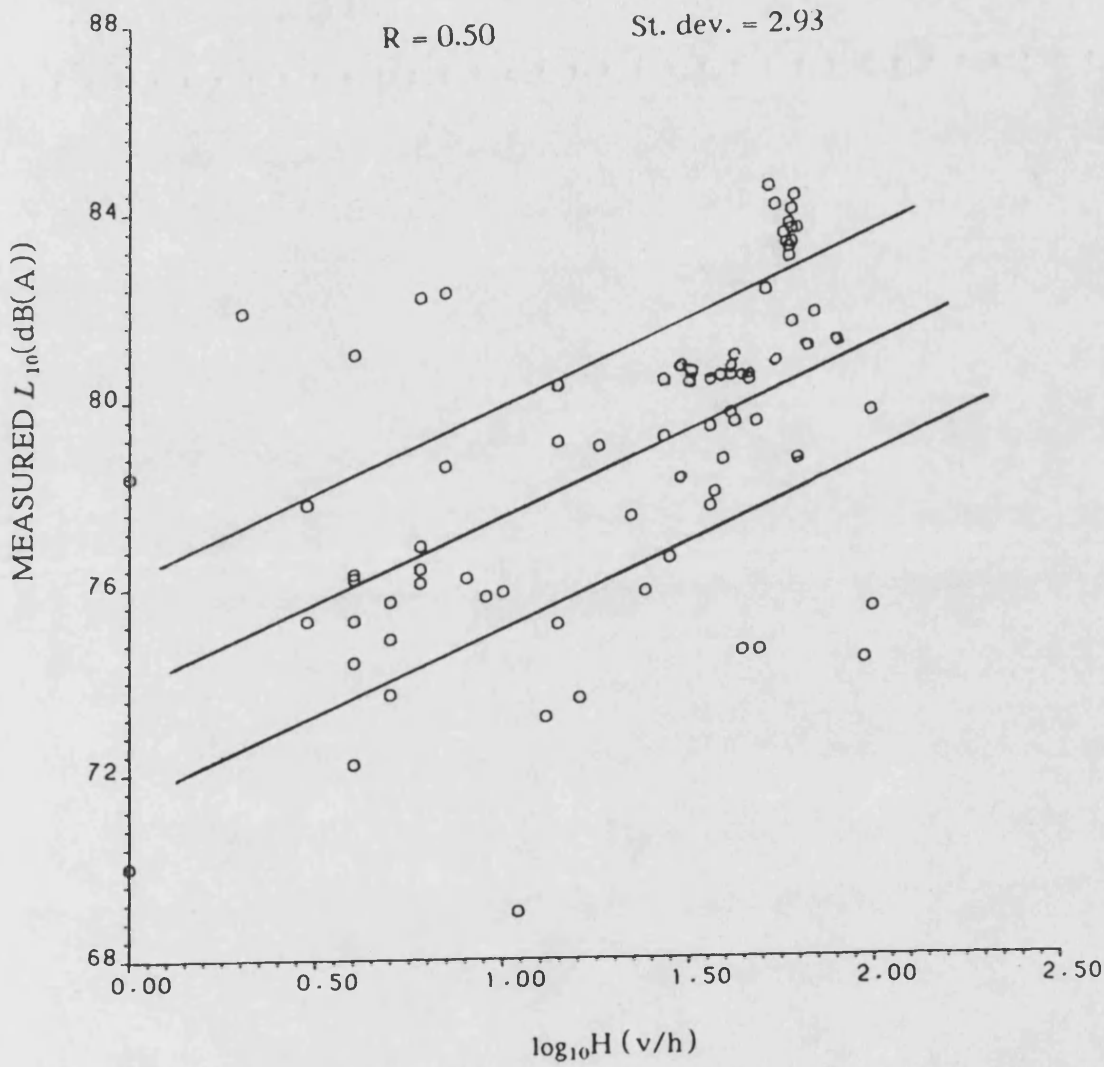


Fig 6.5 Measured L_{10} - heavy vehicles relationship (Equation 6.4) with 95% confidence limits (85 sites)

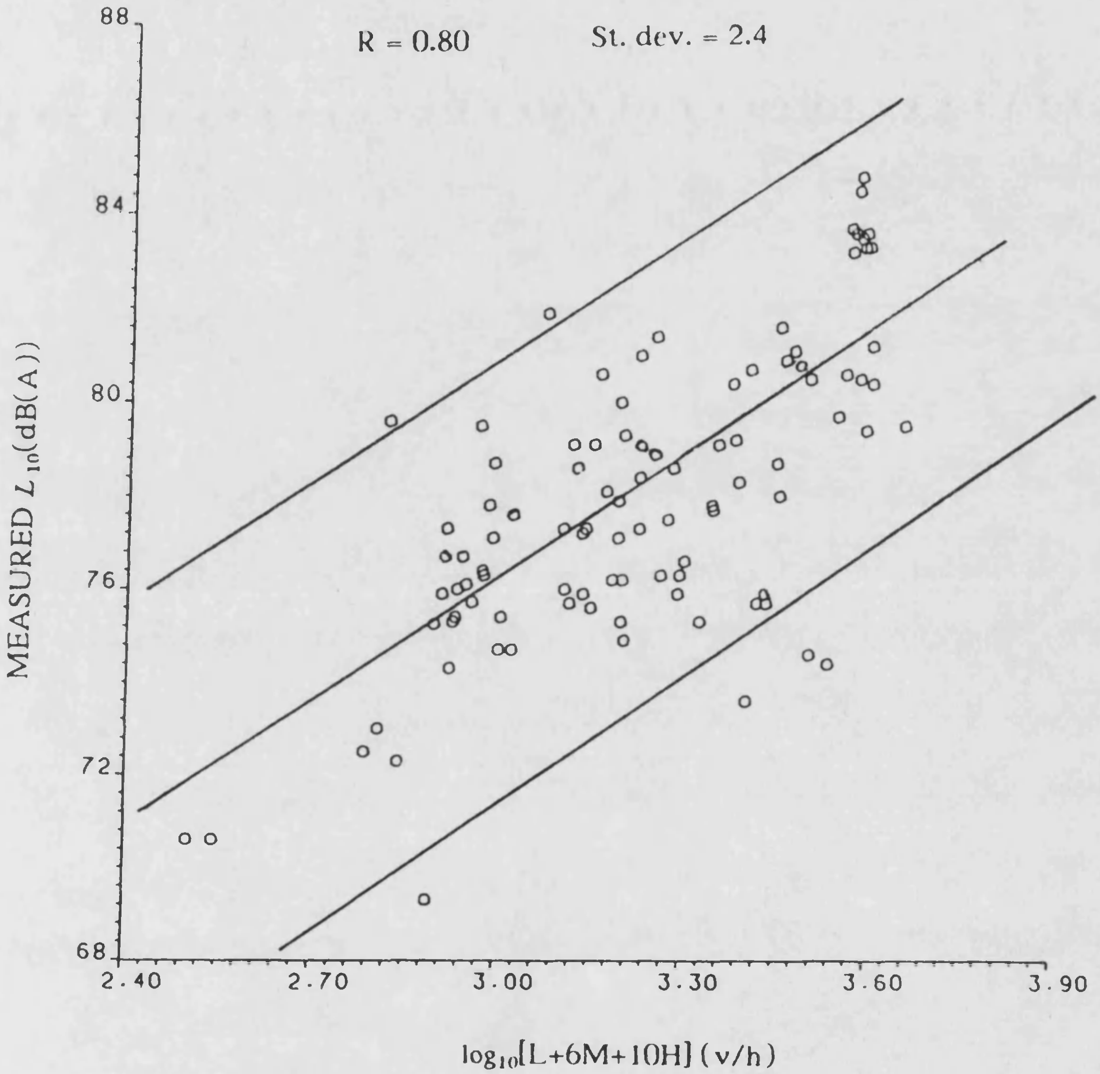


Fig 6.6 Measured L_{10} - traffic composition relationship (Equation 5.5) with 95% confidence limits

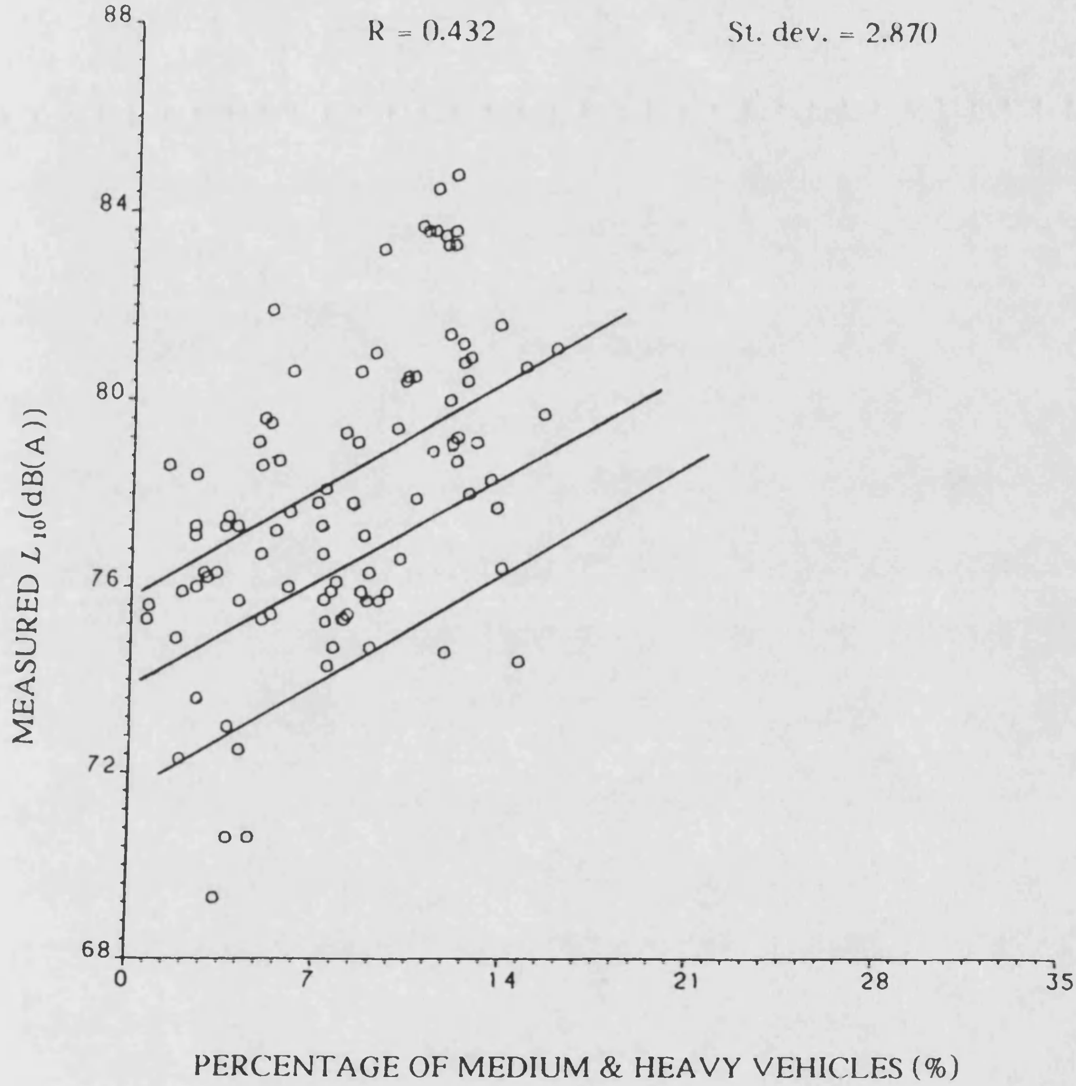


Fig 6.7 Measured L_{10} - percentage of medium & heavy vehicles relationship (Equation 6.6) with 95% confidence limits

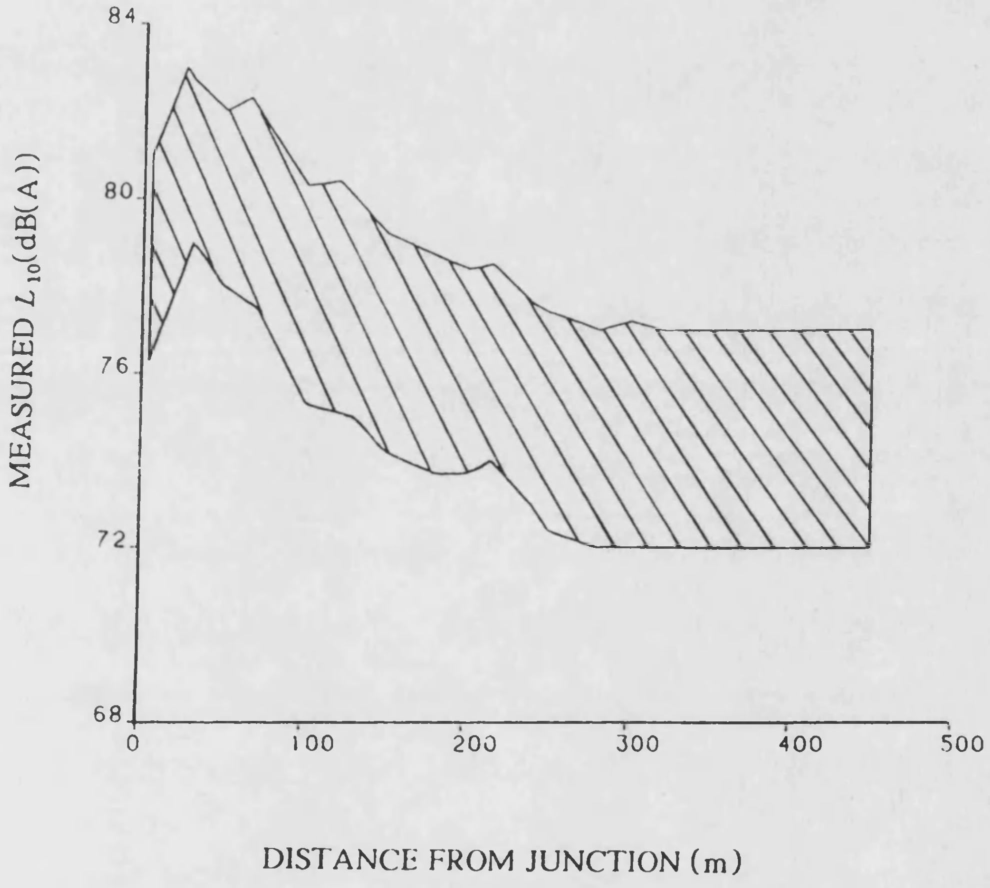


Fig 6.8 Envelope showing typical variation of L_{10} with distance from various junctions for accelerating urban traffic, under different conditions.

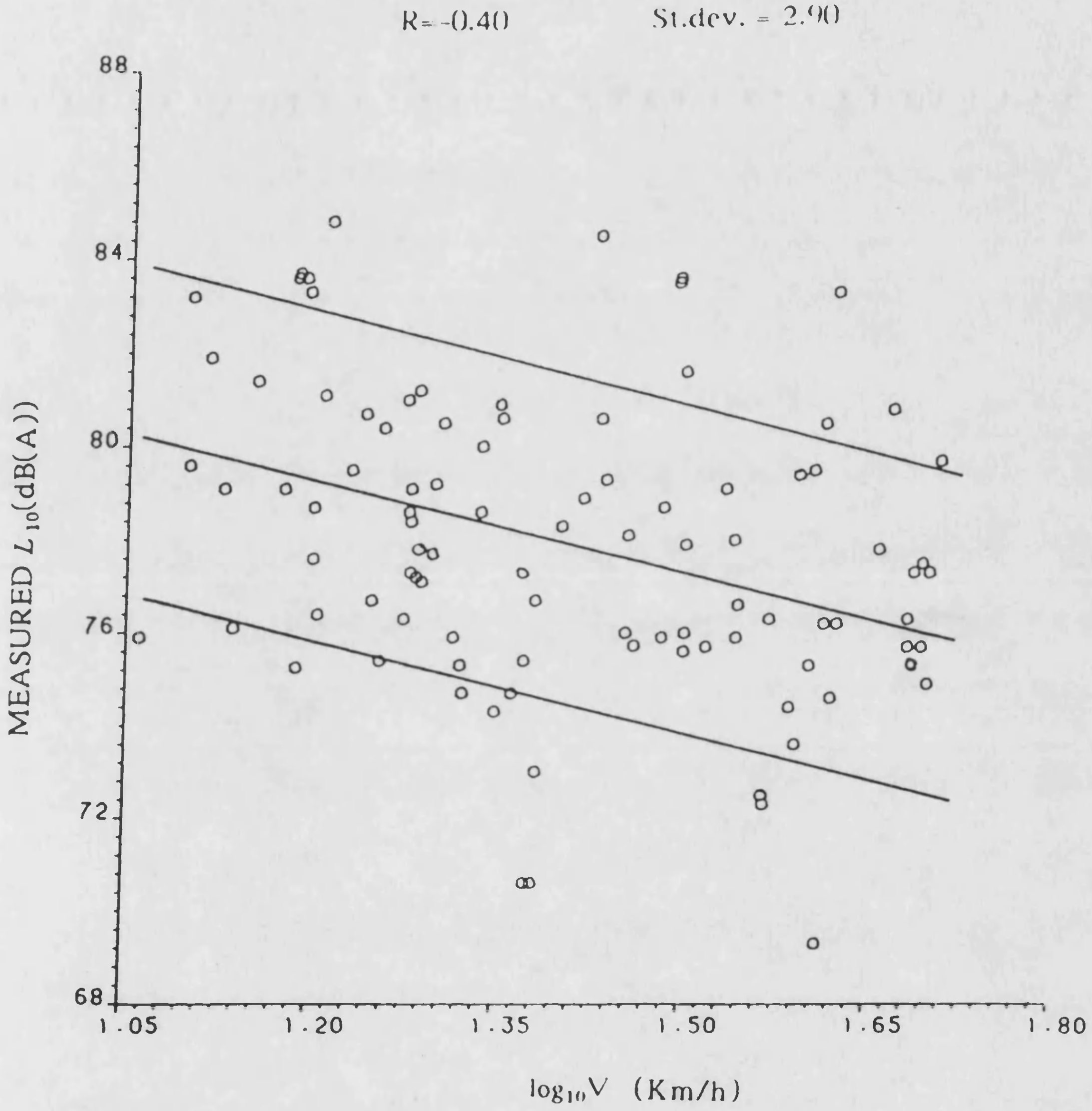


Fig 6.9 Measured L_{10} - mean traffic speed relationship (Equation 6.7) with 95% confidence limits.

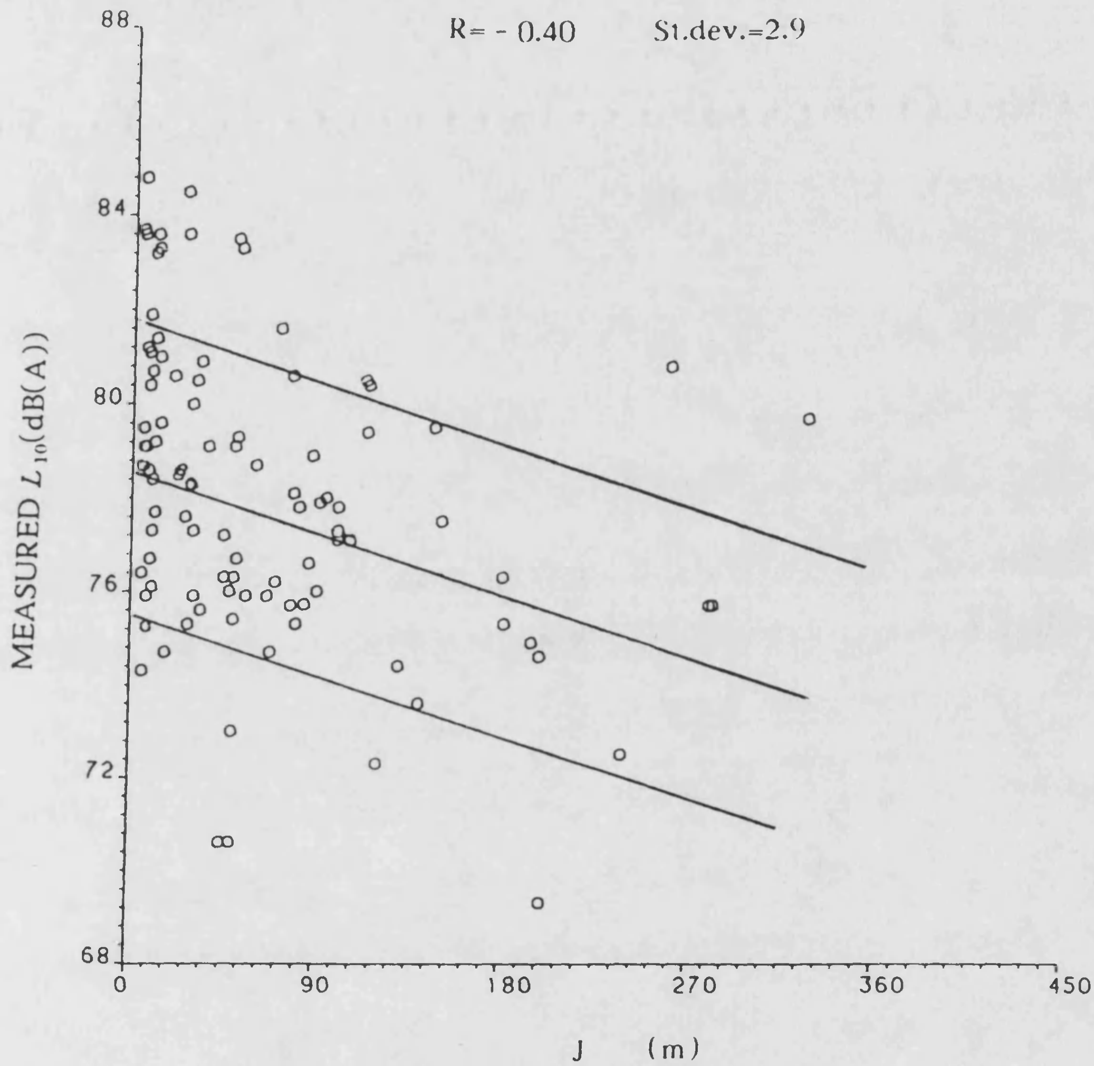


Fig 6.10 Measured L_{10} - distance from junctions relationship (Equation 6.8) with 95% confidence limits.

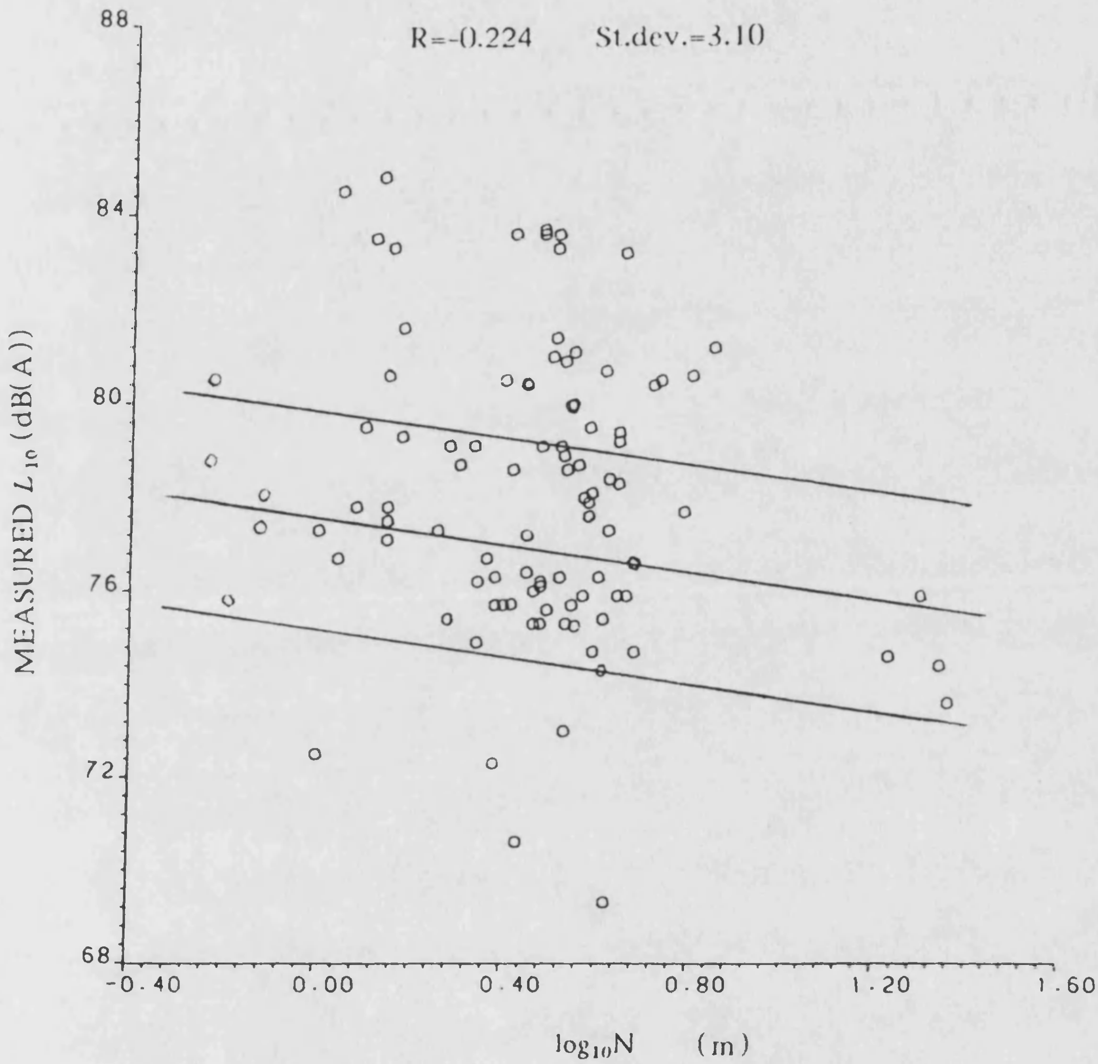


Fig 6.11 Measured L_{10} - distance from nearside building facade relationship (Equation 6.9) with 95% confidence limits.

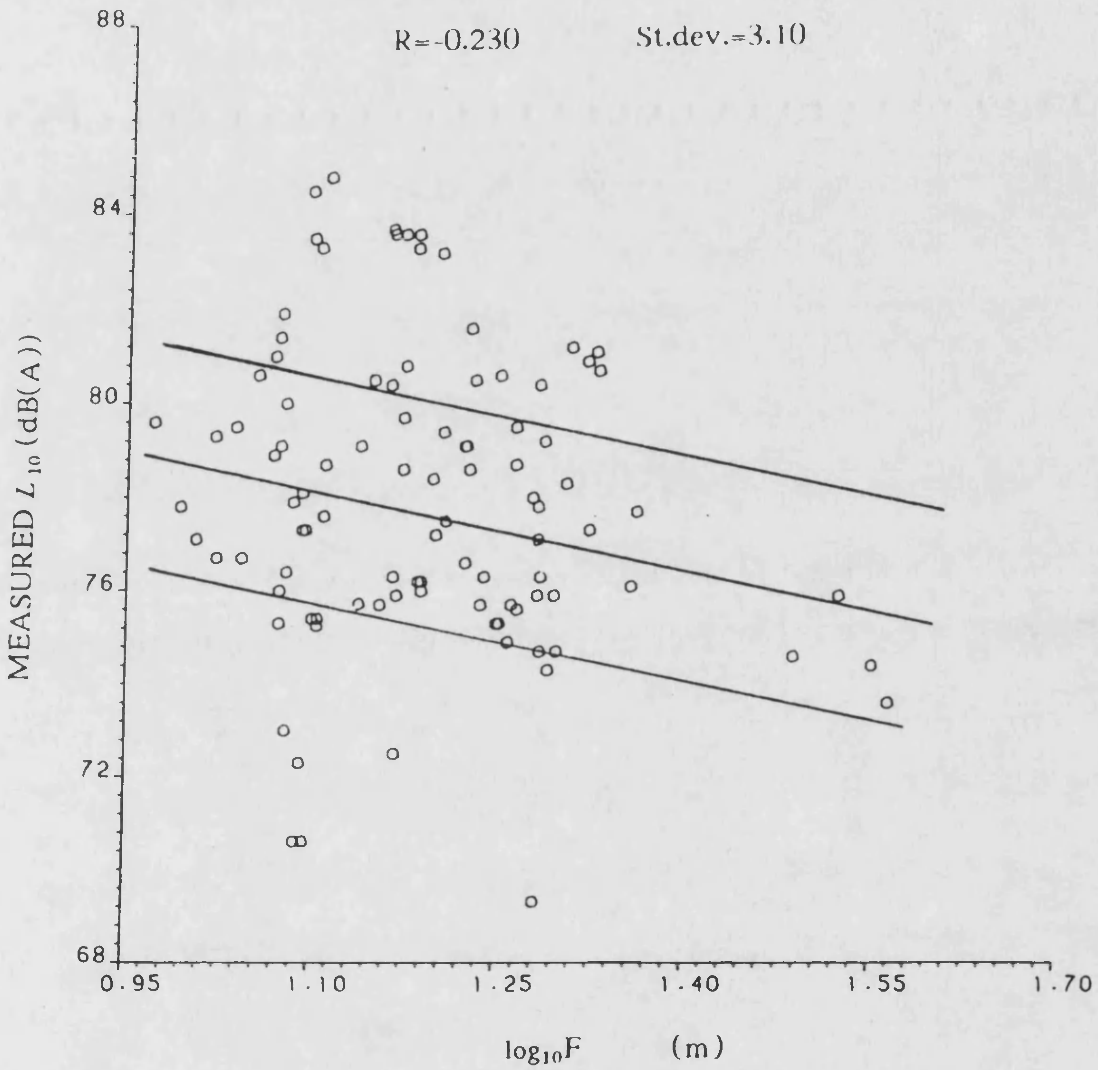


Fig 6.12 Measured L_{10} - distance from farside building facade relationship (Equation 6.10) with 95% confidence limits.

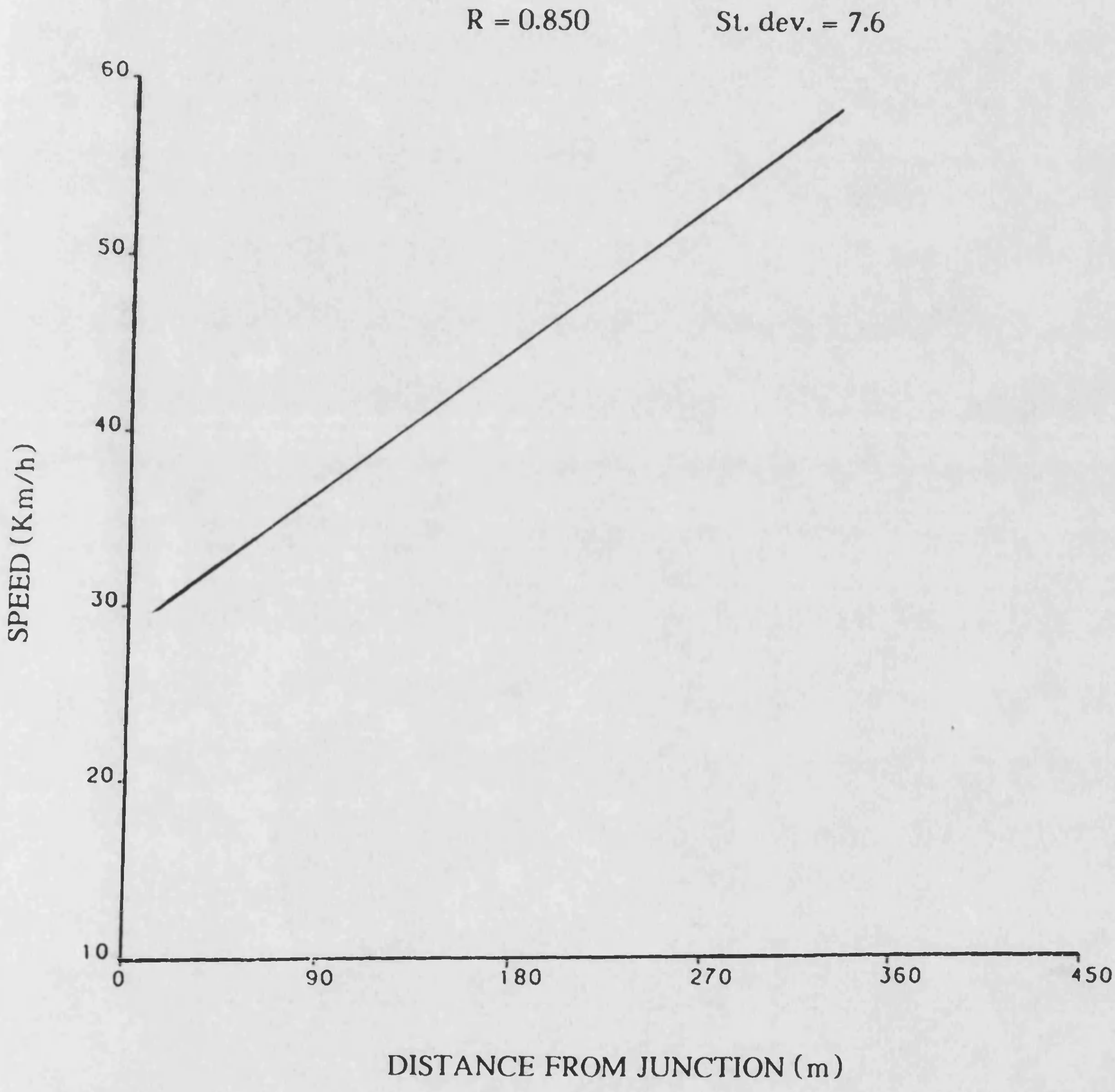


Fig 6.13 Traffic speed - distance from junctions relationship (Equation 6.11)

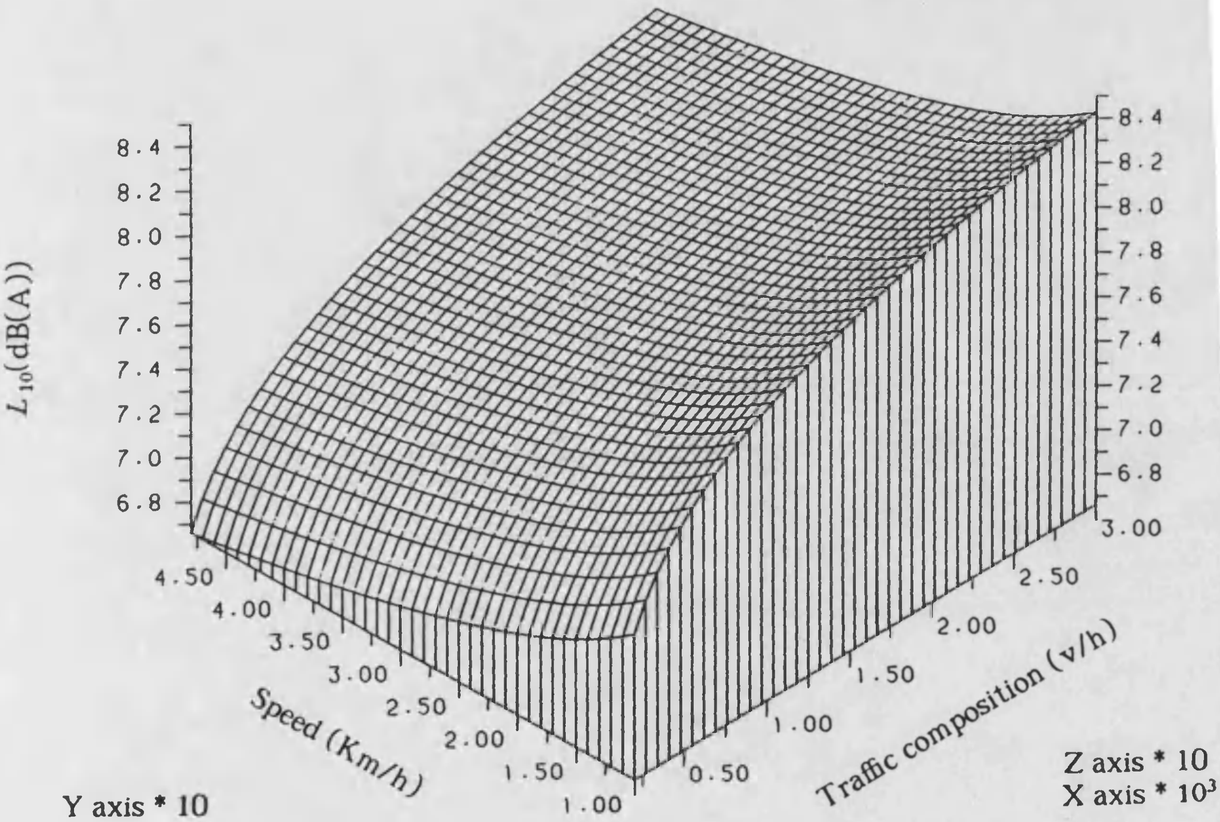


Fig 6.14 Three-dimensional representation of L_{10} as a function of traffic composition and speed (Equation 6.12)

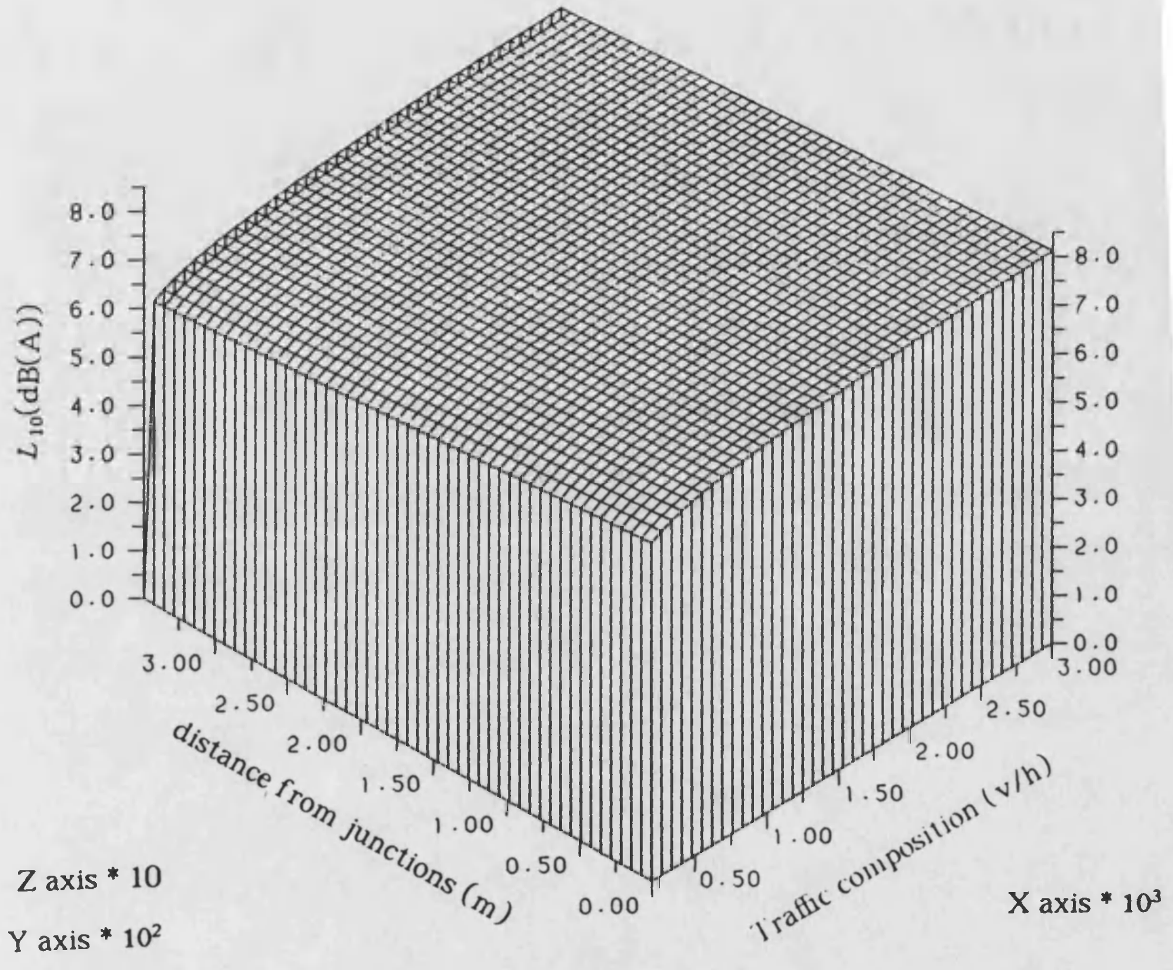


Fig 6.15 Three-dimensional representation of L_{10} as a function of traffic composition & distance from junctions (Equation 6.13).

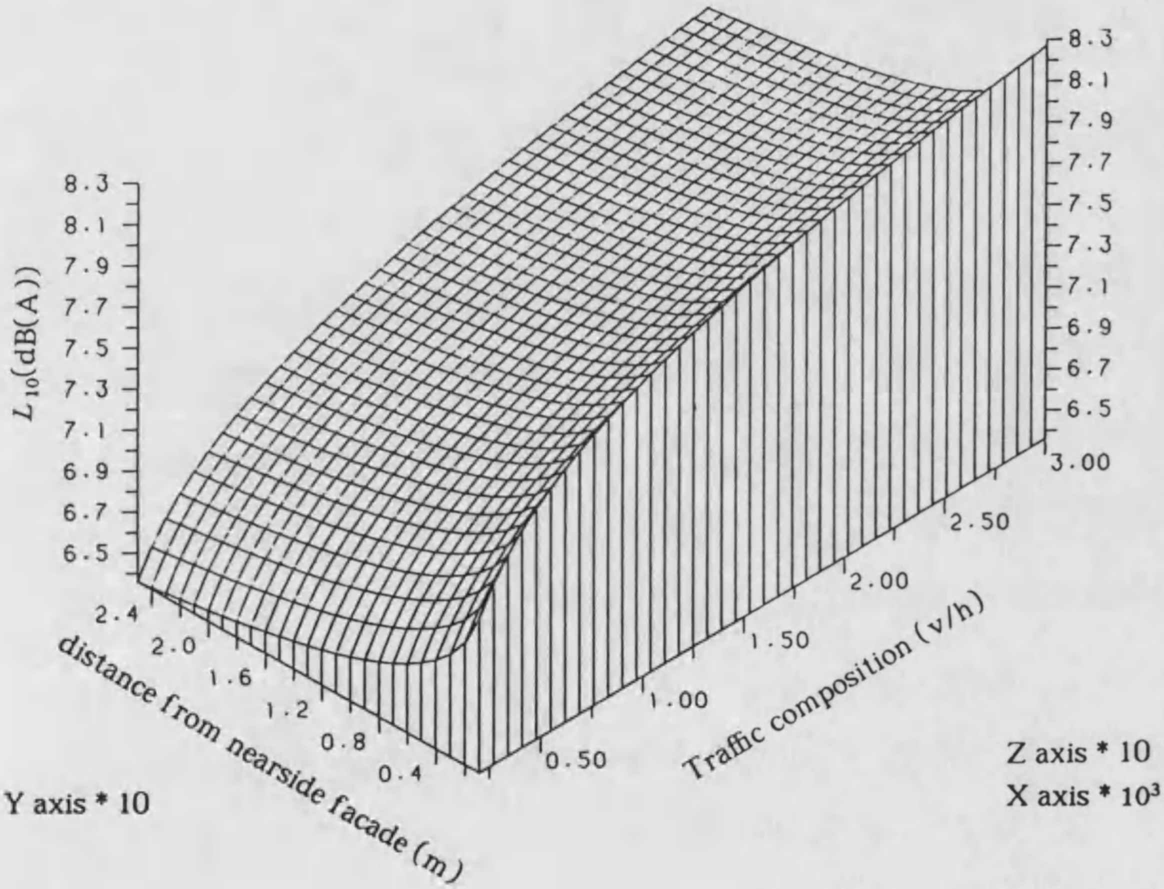


Fig 6.16 Three-dimensional representation of L_{10} as a function of traffic composition and distance from nearside building facade (Equation 6.14)

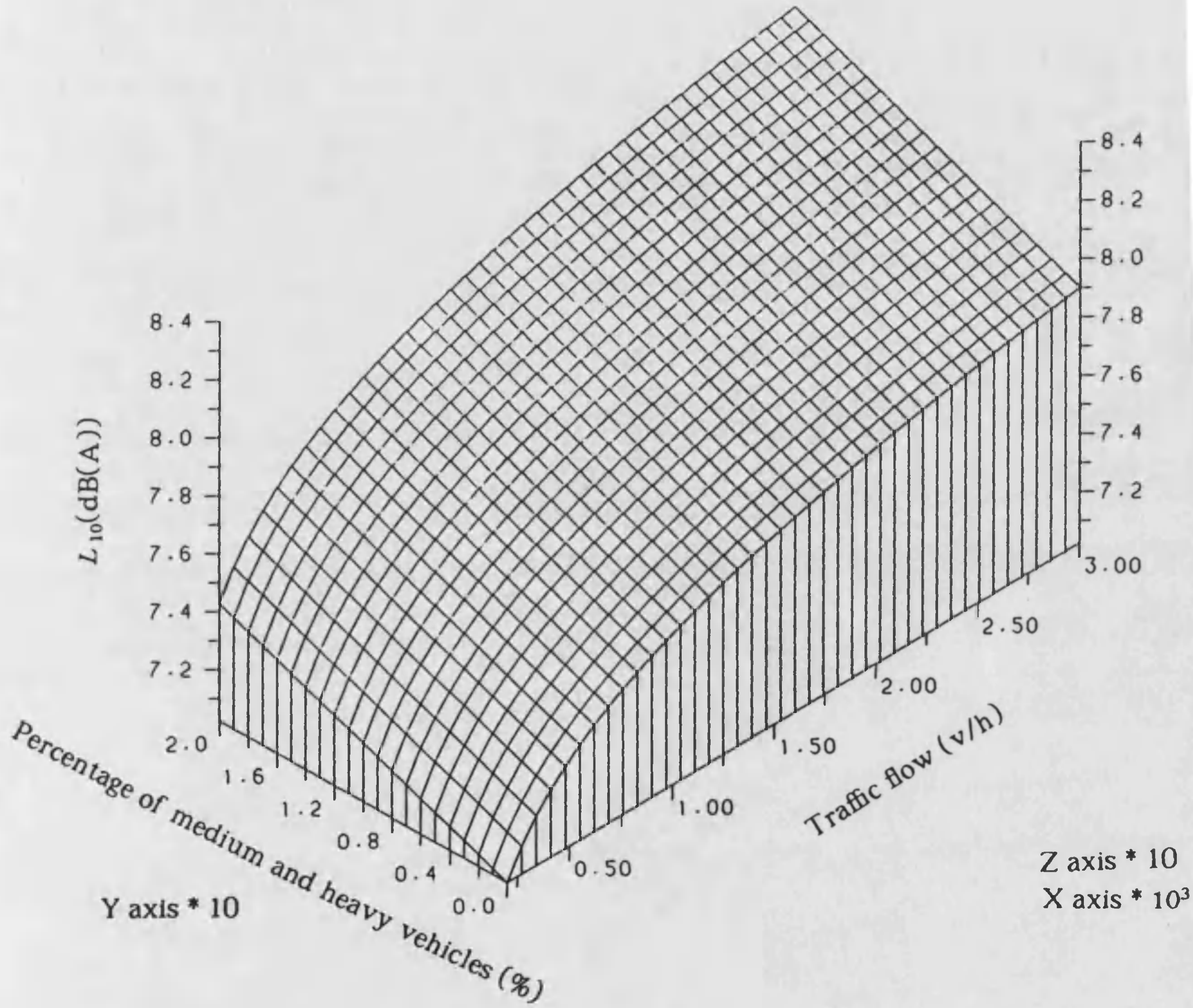


Fig 6.17 Three-dimensional representation of L_{10} as a function of traffic flow and percentage of medium & heavy vehicles (Equation 6.15)

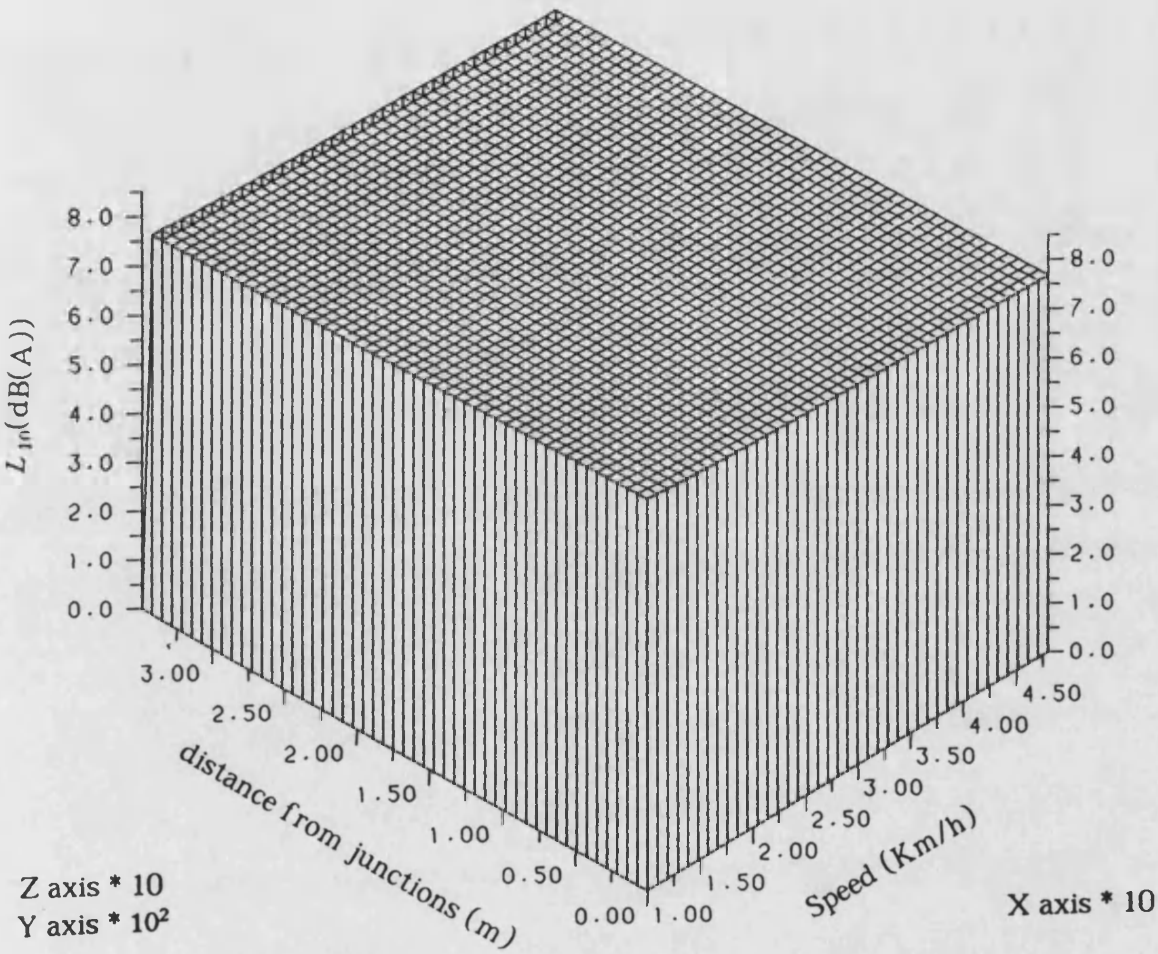


Fig 6.18 Three-dimensional representation of L_{10} as a function of of speed and distance from junctions (Equation 6.16)

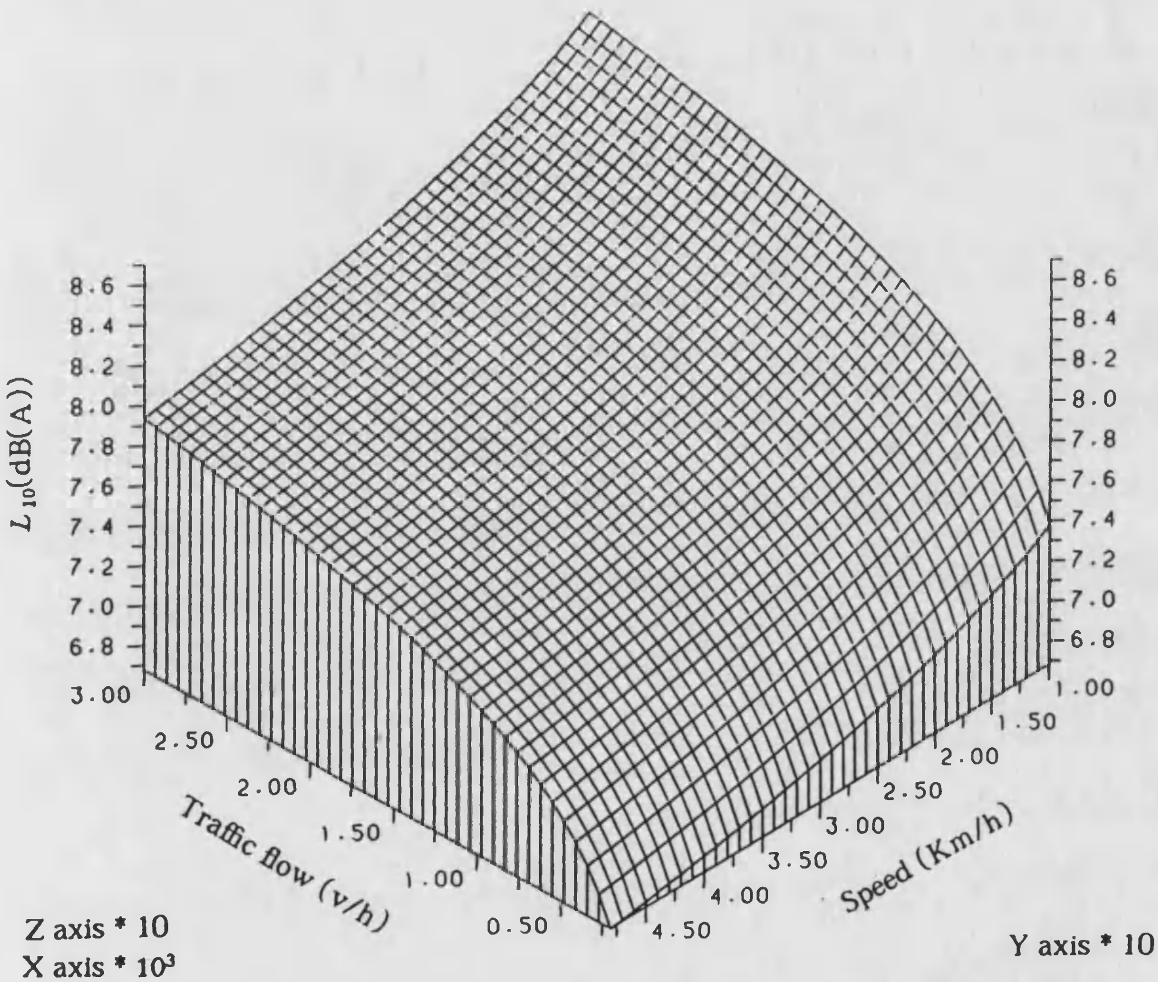


Fig 6.19 Three-dimensional representation of L_{10} as a function of traffic flow & speed (Equation 6.17)

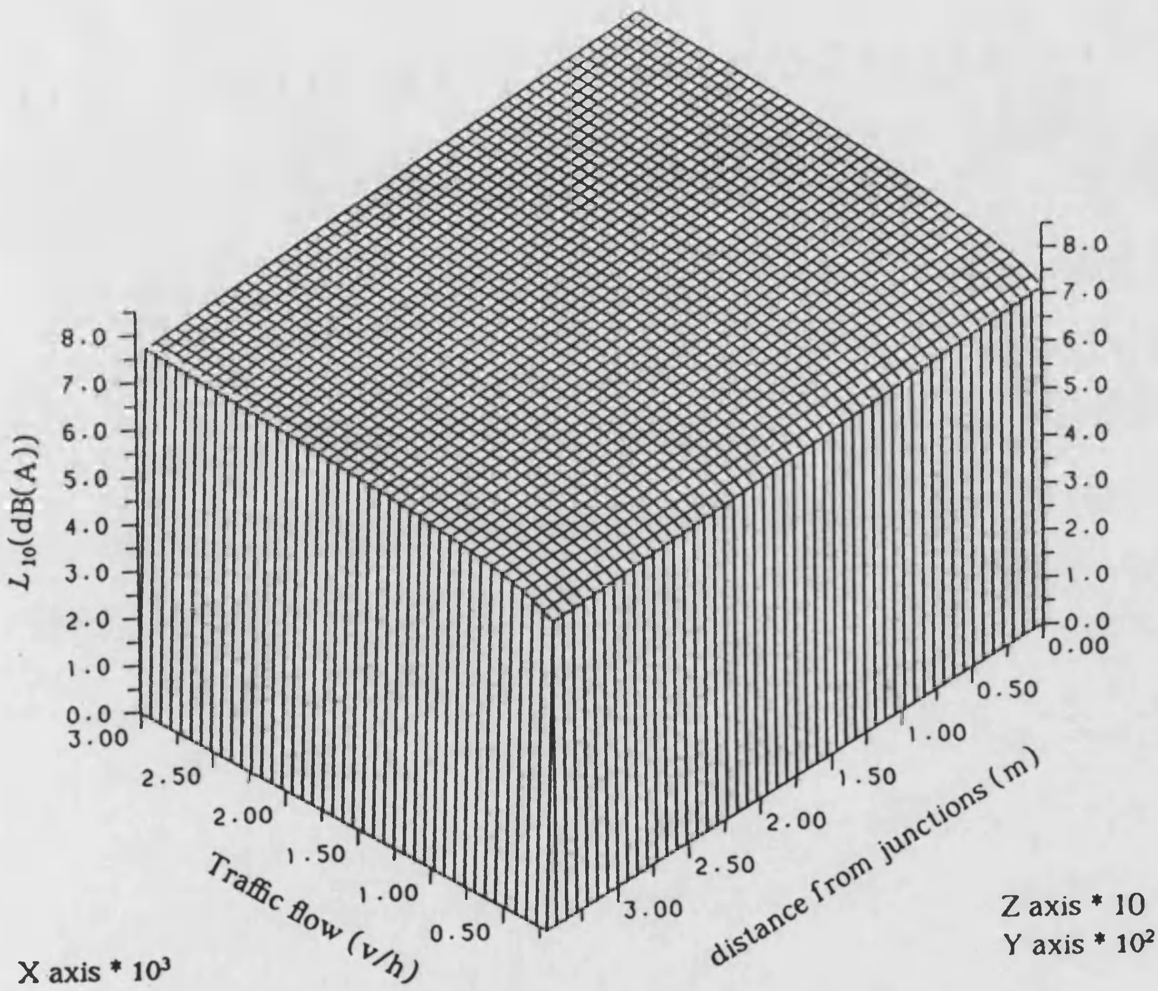


Fig 6.20 Three-dimensional representation of L_{10} as a function of traffic flow & distance from junctions (Equation 6.18)

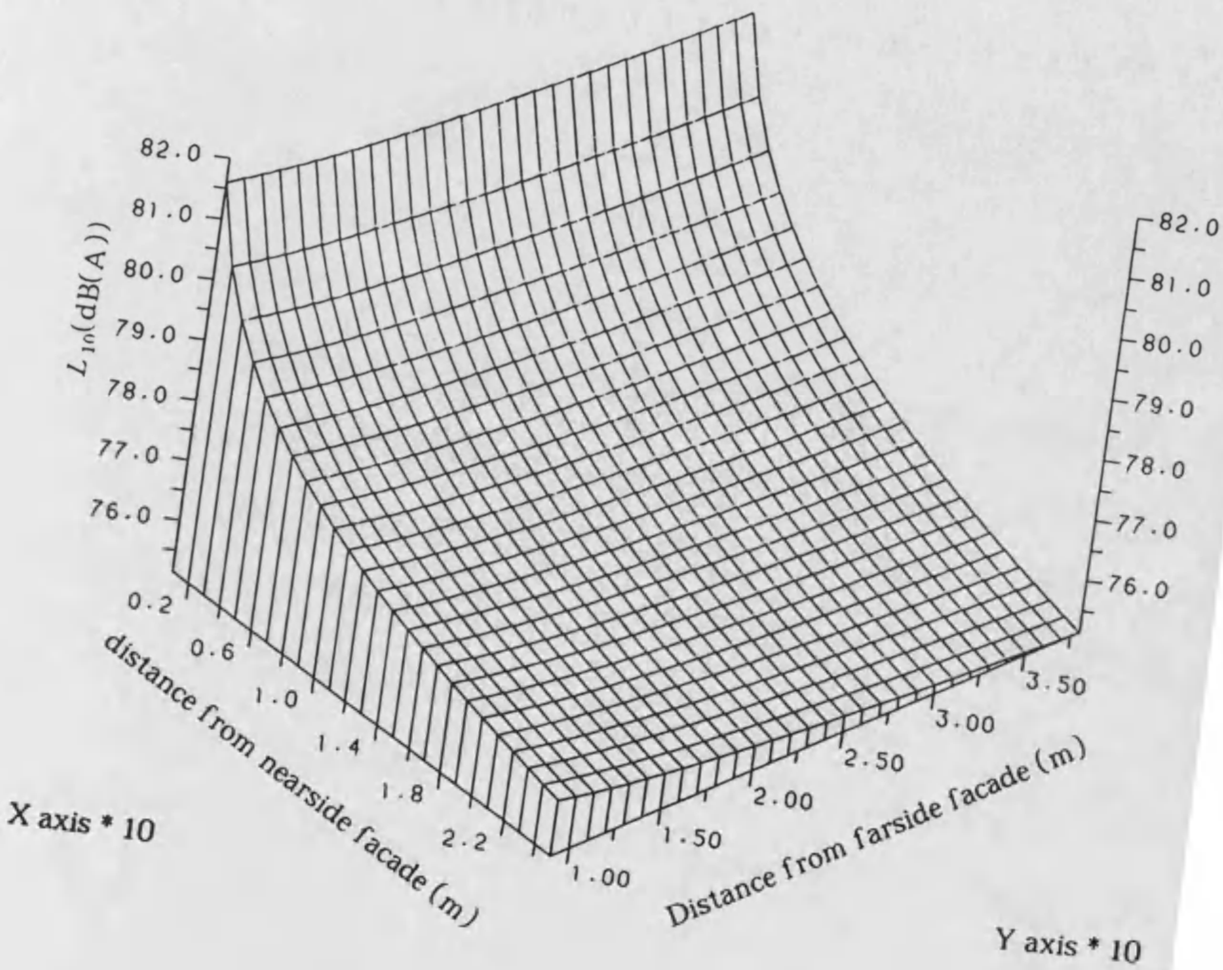


Fig 6.21 Three-dimensional representation of L_{10} as a function of nearside & farside building facades (Equation 6.19)

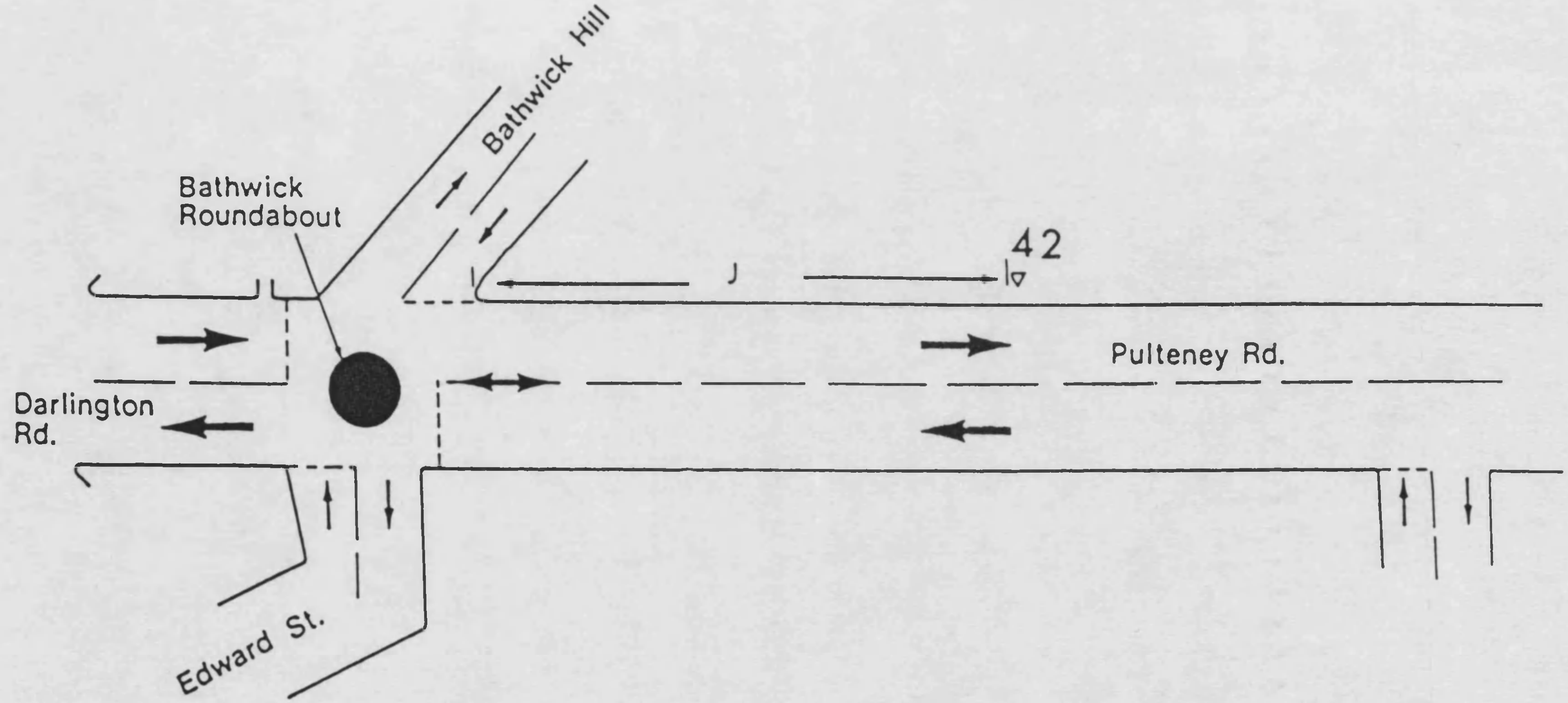


Fig 6.22 Location of measurement point near Bathwick roundabout
(Node no. 5)

J Distance between measurement point and roundabout

▽ Measurement position (site no. 42, accelerating stream of traffic)

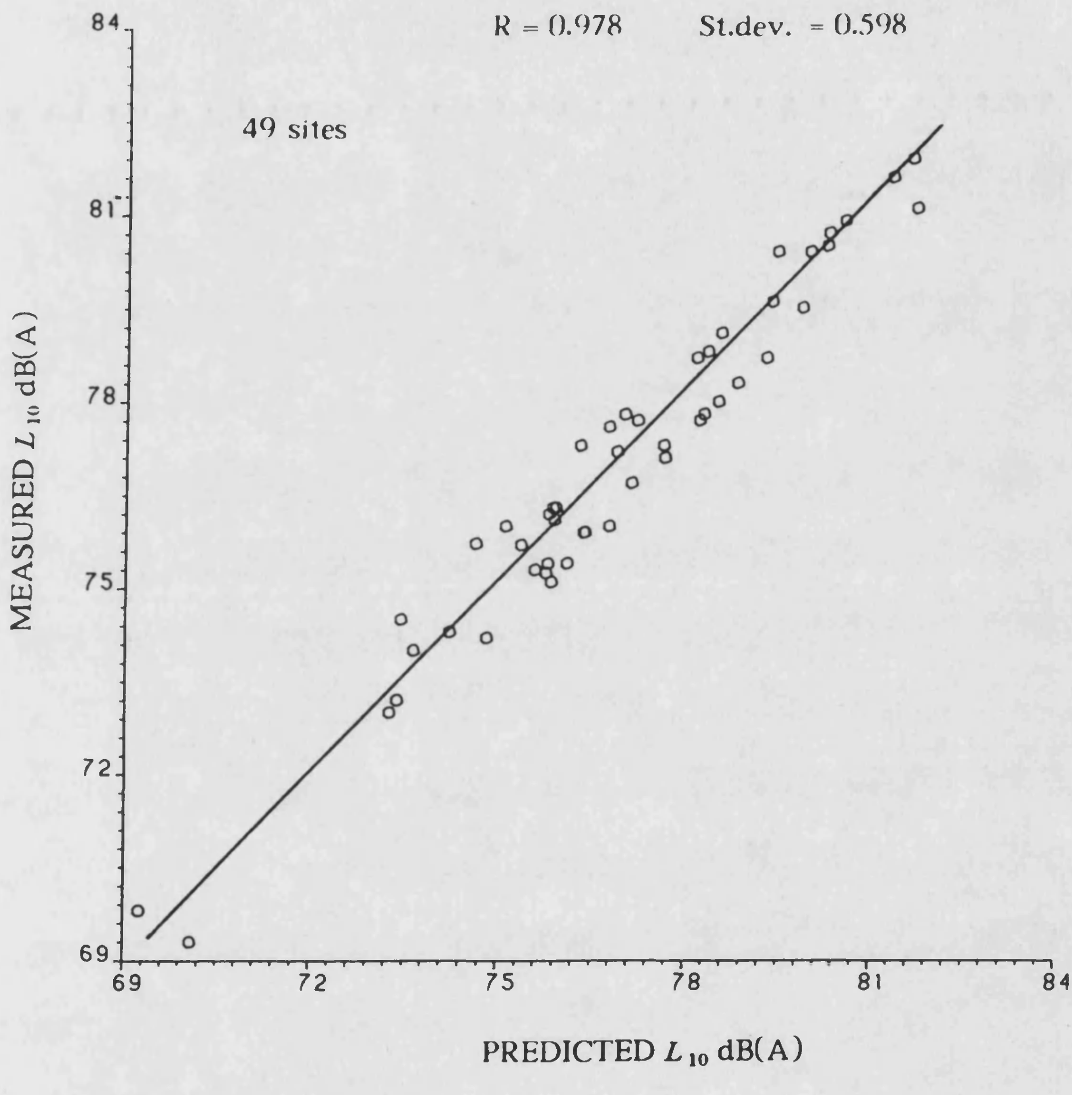


Fig 6.23 Measured L_{10} versus L_{10} predicted by roundabouts model (Equation 6.20)

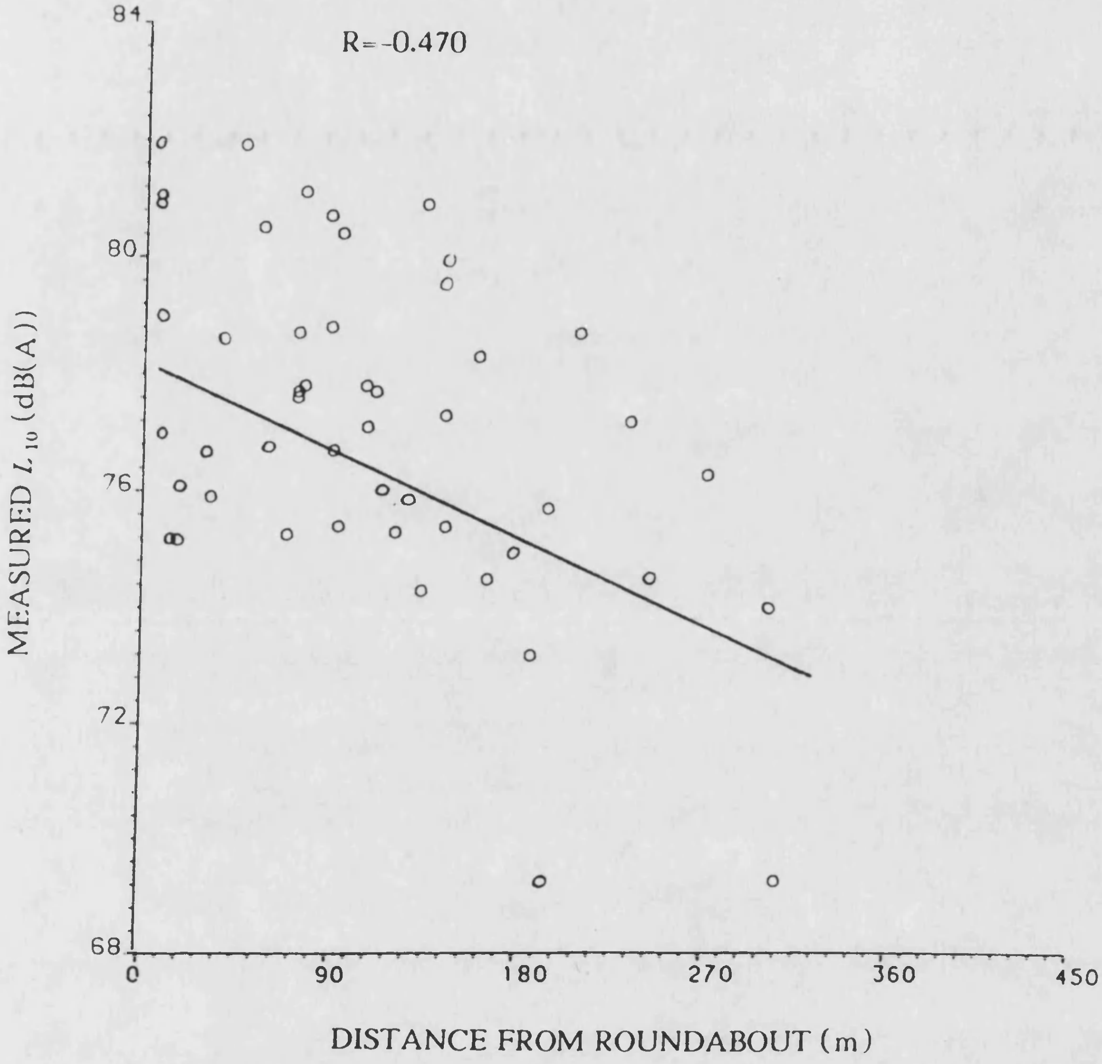


Fig 6.24 Measured L_{10} versus distance from roundabouts

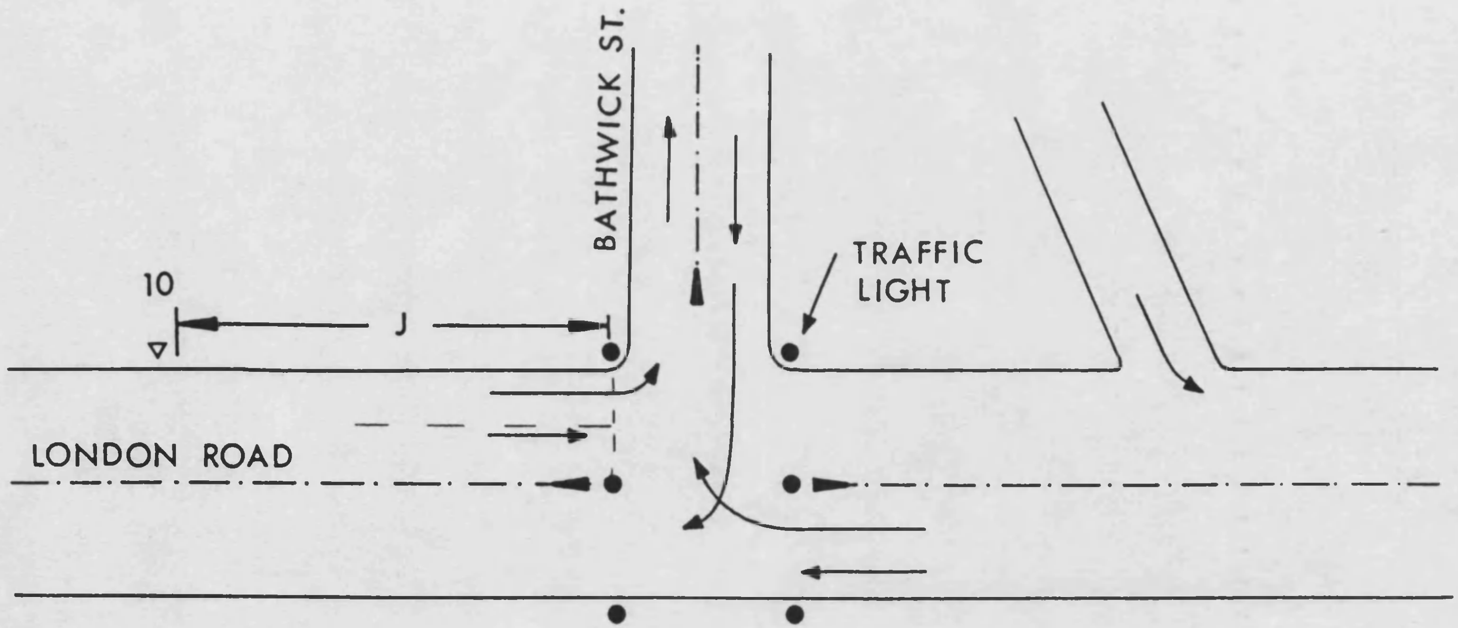


Fig 6.25 Location of measurement point near London Road traffic light intersection (Node no. 1)

J Distance between measurement point and traffic light intersection

▽ Measurement position (site no.10, decelerating stream of traffic)

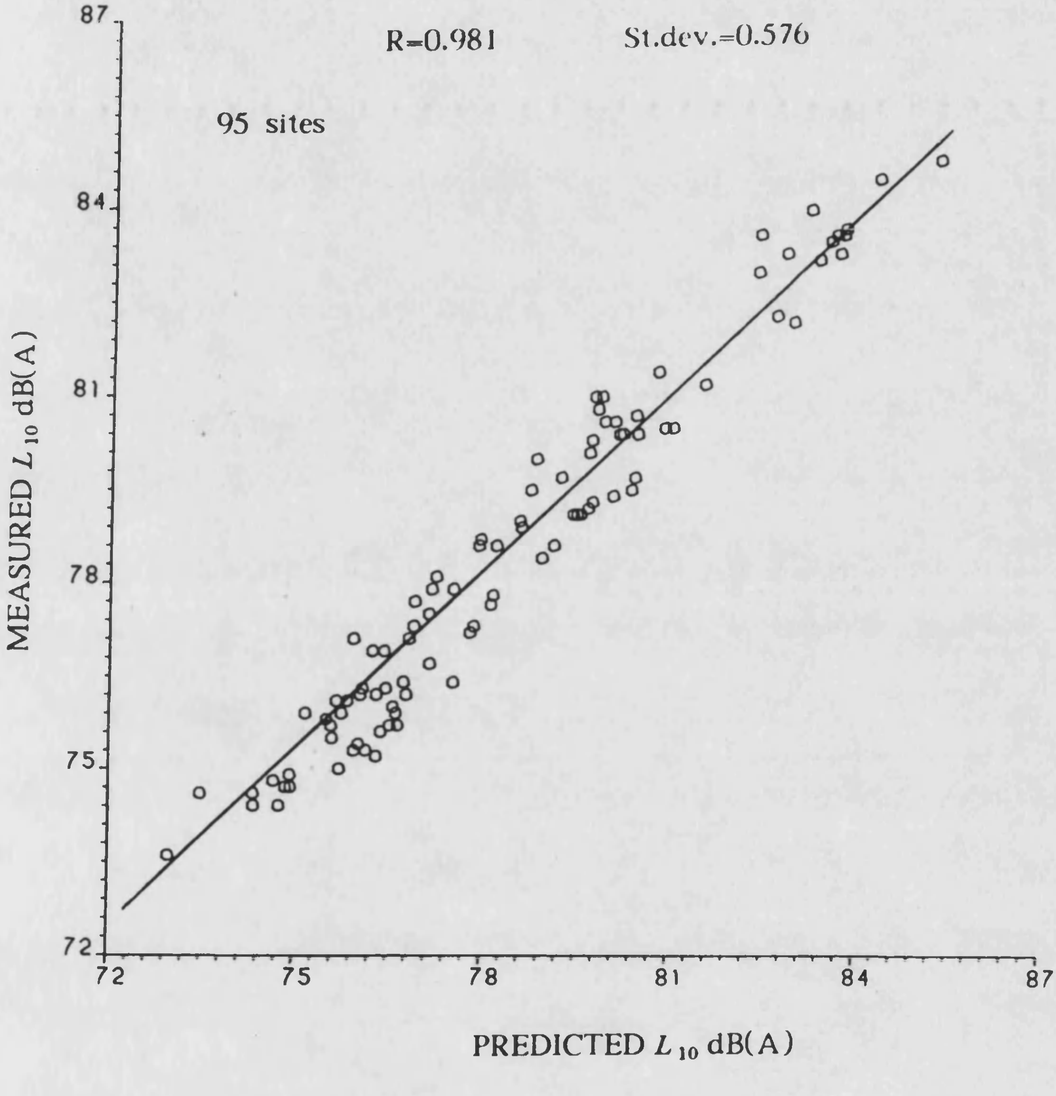


Fig 6.26 Measurement L_{10} versus L_{10} calculated by traffic light intersections model (Equation 6.21)

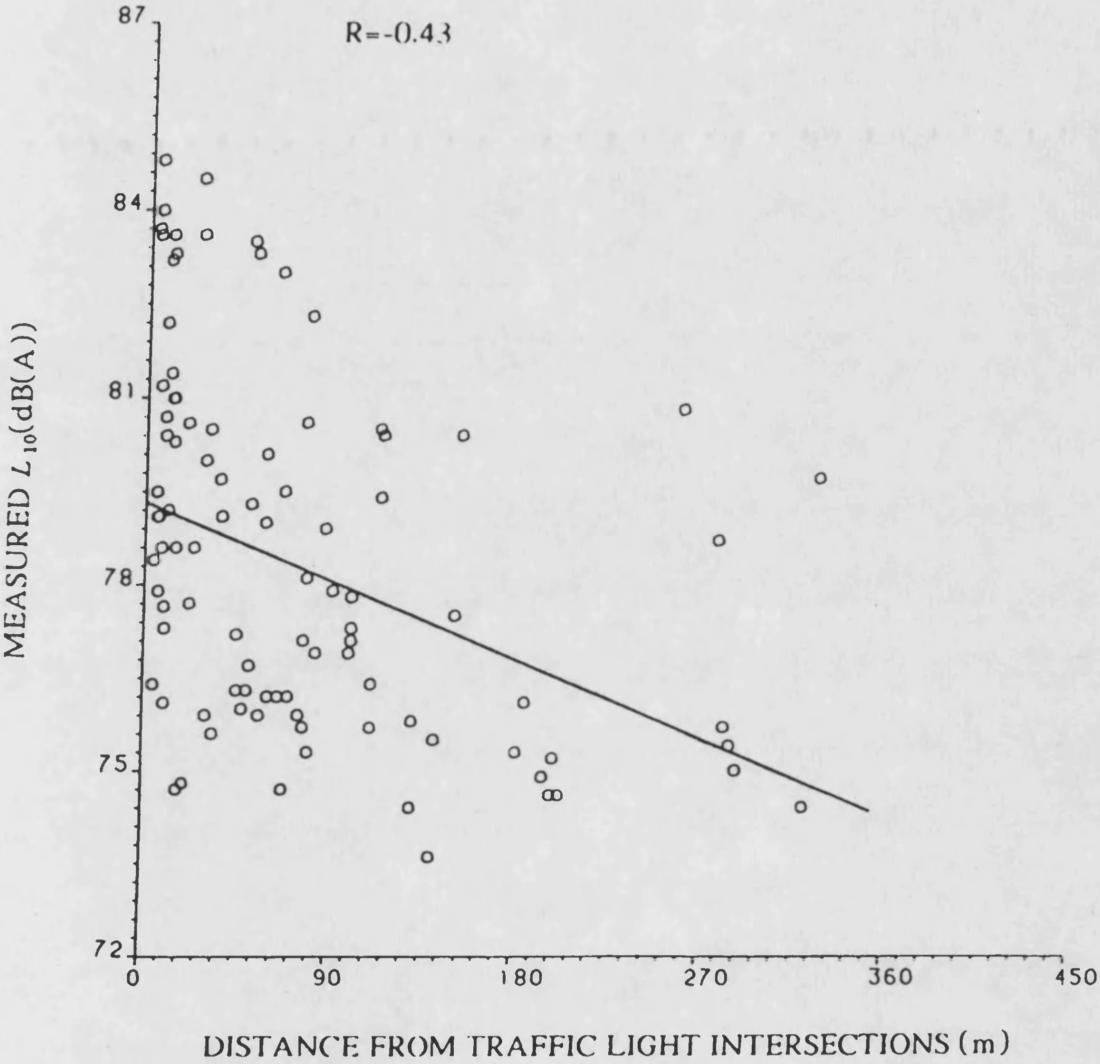


Fig 6.27 Measured L_{10} versus distance from traffic light intersections

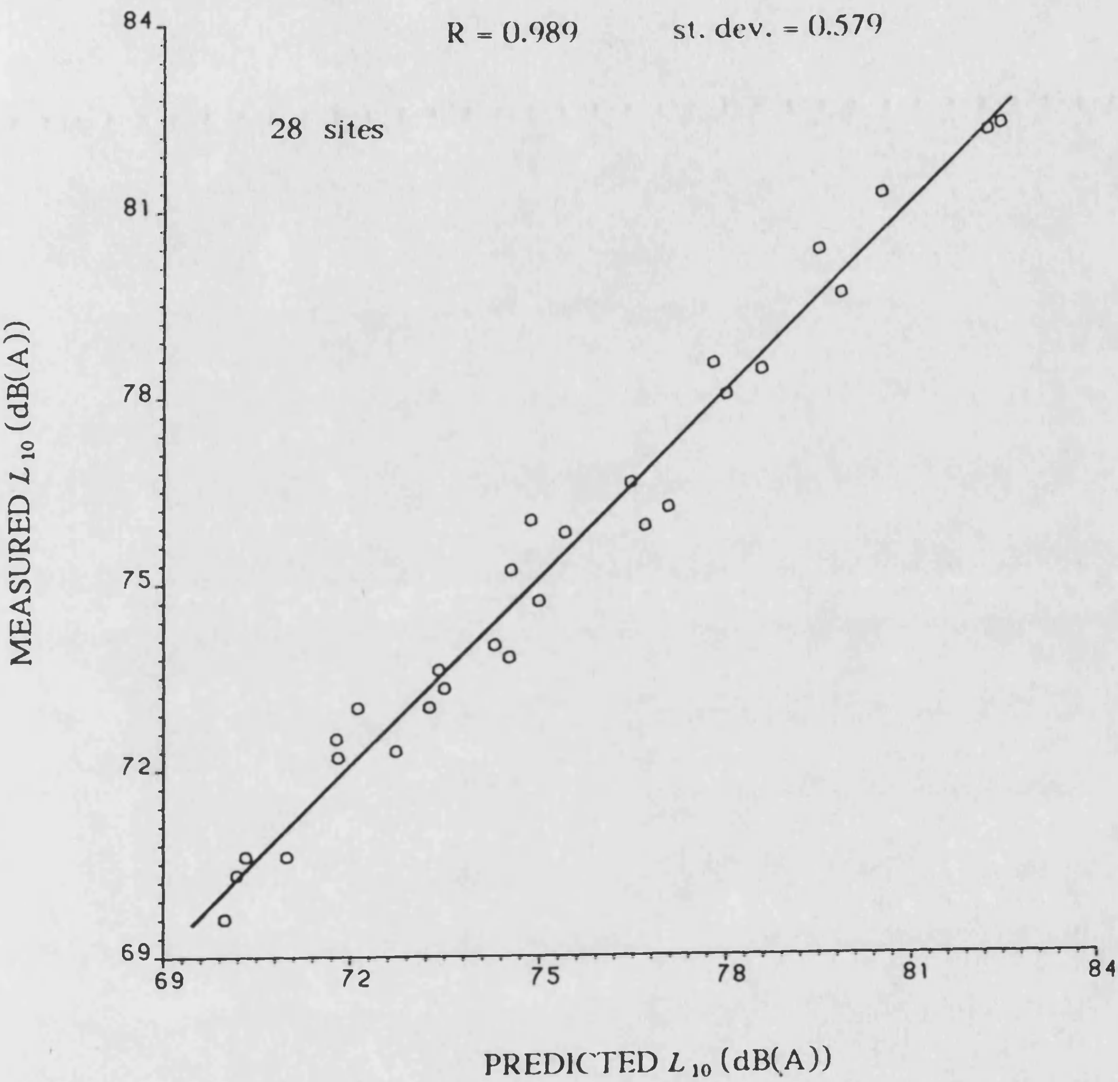


Fig 6.28 Measured L_{10} versus L_{10} calculated by priority junctions model (Equation 6.22)

CHAPTER SEVEN

DEVELOPMENT OF OVERALL PREDICTION MODELS

7.1 INTRODUCTION

The earlier chapters have shown that there is an urgent need to forecast accurately and assess existing and future traffic noise levels and their influence on urban and suburban areas. In order to predict levels of noise it is necessary to develop means of predictions showing the relationship between noise indices and features of built-up areas. This development will assist planners and designers to include traffic noise as one of the variables to be taken into account in planning, in order to minimise the negative effects of traffic on the environment.

The objective of this chapter, therefore, is to establish the best models including noise levels and as many variables combined as possible in areas where conditions vary, by gathering a comprehensive data. The significance of this modelling is as follows: an inspection of the relationships between urban noise levels and the selected variables showed that the correlation coefficient increased significantly when the overall relation was employed in the computations (Chapter 6). There is a partnership between traffic noise and urban parameters which makes their separation unsatisfactory. A review of the literature in this field has shown that development of a reliable prediction model requires many if not all urban factors to be included (Chapters 3 and 4).

The emphasis in the analysis was on the establishment of models for predicting the L_{10} and L_{eq}. This was because of the position of these indices in current regulations and planning practice and because of their superiority over other indices which was defined in Chapter 6.

In order to develop a comprehensive prediction tool, various kinds of models have been built. The models are the subject of this chapter which is split into several sections as follows:

(1) Selection of measurement sites.
(2) Development of a prediction model for road transport noise in urban areas (L_{10}).
(3) Development of a prediction model for road transport noise in suburban and urban areas (L_{10}).
(4) Development of prediction models for road transport noise (L_{eq}) in built-up areas.
(5) Reliability of present noise prediction methods.
(6) Buildings and traffic noise propagation.
(7) L_{50} and L_{90} prediction models.
(8) Advantages of all the developed prediction models

7.2 SELECTION OF MEASUREMENT SITES

204 sites were chosen along various road networks in Bath's urban and suburban areas. They were selected according to specific criteria (see Chapters 5 and 6) and assumed to fall into two categories:

(1) Urban area sites: 172 locations were chosen in the urban area. They covered five types of land use. The main types of traffic were classified as light, medium and heavy. 48 km/h, as an urban speed restriction, existed in all sites (see Figure 6.1).
(2) Sites of suburban principal routes: 32 positions were selected in Bath's suburban areas. They were subject to a 64 km/h speed limit, and were

selected with roughly similar types of layout structure to the above urban locations. Three traffic light intersections and two uncontrolled roundabouts were included. The maximum distance between measurement point and junctions was extended to 420 m. Heavy traffic conditions existed at all of the sites. Figures 7.1 and 7.2 illustrate the typical distribution of these sites.

Procedures for L_{eq} and L_{10} measurement have been previously investigated (Chapters 4-6). These were followed throughout this chapter. The data collected from the above sites were used to develop the following prediction methods for various specifications.

7.3 PREDICTION MODEL FOR ROAD TRANSPORT NOISE (L_{10}) IN URBAN AREAS (URBAN MODEL)

7.3.1 Model development

The measurements of urban areas which were made at 172 sites, have provided an opportunity to study the dependence of L_{10} dB(A), due to urban traffic as a function of traffic, road and building parameters. Many prediction models were obtained during the period of this study. They ranged from simple to most complex. The following model was chosen for its accuracy and simplicity.

By using the NFNOS computer program which is based upon multiple regression analysis and the MINITAB system (see Section 6.2), the best final urban prediction model relating L_{10} dB(A) to the combined variables was:

$$L_{10} = 57.0 - 5.60 \log_{10}V - 5.39 \log_{10}F - 0.0108 J + 11.7 \log_{10} (L + 6M + 10H) - 4.00 \log_{10} (d - k) \quad \ldots (7.1)$$

where:

$R = 0.981$

St. Dev. = 0.624

Residual = ± 1.3 dB(A) for 98% of the sites

V = Mean speed of traffic (km/h)

F = The distance between measurement point and farside building facade ($F=K+W+X$) (m)

K = The distance between measurement point and nearside kerbside (i.e, 1m)

W = The road width (m)

X = The distance between farside building facade and the farside kerb (m)

J = The distance from the relevant junction (m)

L,M,H = The numbers of light, medium and heavy vehicles (v/h)

d = The distance between nearside kerb and nearside facade (m)

The 'Urban Model' was originally developed in terms of W instead of F and showed significant correlation (see Section 9.7.2). In order to make it more thorough, the model was modified to the above structure.

This model is significant. It is required for the conditions where the speed below 48 km/h and traffic composition, i.e, L, M and H affects the environment significantly.

7.3.2 Model evaluation

7.3.2.1 Statistical evaluation

Based on the following results obtained from the computation, the Urban

Model represents a significant tool for prediction of noise level in terms of the combined independent variables.

(1) Significant correlation coefficient, R=0.981 (The critical value of R = < 0.159 at the 0.05 level of significance and R = < 0.208 at the 0.01 level).

(2) Based on a residual analysis, E=± 1.3 dB(A) for 98% of the sites, the model appears to be adequate.

(3) A 99% confidence interval estimate was employed to check the significance of the relationship between the measured L_{10} dB(A) values and the L_{10} values predicted by the model. The objective was to set up a 99% confidence interval estimate of the true slope of the relationship and to determine whether the null hypothesis value is included in the interval. The following formula was used (Berenson and Levine, 1983).

$$b_1 \pm t S_{b_1}$$

where b_1 is the coefficient of the predicted value, S_{b_1} is the standard deviation of the coefficient and t is the critical value of t-distribution corresponding to a 0.01 upper tail area, at an appropriate degree of freedom (df).

The true slope is estimated with 99% confidence to be between +1.04 and +0.96. These values are clearly above zero (the null hypothesis has been rejected). Had the interval included zero, no relationship would have been determined. The conclusion is that there is a significant positive relationship between measured values and values predicted by the Urban Model with 99% confidence. Figure 7.3 shows measured L_{10} versus L_{10} calculated by the Urban Model.

(4) A test of a null hypothesis was also employed to check the significance of the urban model by comparing:

$$\text{the Variance Ratio, VR} = \frac{MeanSquare\ ,MS\ ,(regression\ )}{MeanSquare\ ,MS\ ,(residual\ )}$$

with the critical value of f-distribution at an appropriate degree of freedom. The VR=328.86/0.390 = 843.23. The f-distribution = $f(5,166)_{0.1\%}$ = < 4.42(5 is the df of regression and 166 is the df of residual, at upper 0.1% tail area of the f-distribution). Thus, the model is significant, since the value of f is much lower than the value of VR. See also Table 7.7.

(5) Each independent variable makes a significant contribution to the model in the presence of the other variables. The contribution is clear in the following analysis of variance obtained (SS=Sum Square).

Predictor	df	SS	MS
$\log_{10}V$	1	494.317	494.317
$\log_{10}F$	1	25.281	25.281
J	1	59.653	59.653
$\log_{10}(L+6M+10H)$	1	735.495	735.495
$\log_{10}(d-k)$	1	336.685	336.685
residual	166	65.351	0.394

$$MS = \frac{SS}{df}$$

$$f(1,166)_{0.1\%} = < 11.38$$

$$VR = \frac{MS\,(predictor\ )}{MS\,(residual\ )} = > \text{f in all cases (significant)}$$

(6) Employment of the variables which were not considered by previous practice (Chapter 4) has caused a significant improvement to the urban model fit. For example, the consideration of V, J and F has increased the R^2 from 62.46% to 96.2% as follows.

Source	df	SS	MS	R^2%
regression 1 ($\log_{10}(L+6M+10H)$, $\log_{10}(d-k)$)	2	1072.18	536.09	62.46
regression 2 ($\log_{10}V$, $\log_{10}F$,J)	3	579.251	193.084	33.74
regression 3 (1 and 2)	5	1651.431	330.286	96.2
residual (1 and 2)	166	65.351	0.394	

$$MS = \frac{SS}{df}$$

$$f(3,166)_{0.1\%} = < 5.79$$

$$VR(\text{regression } 2) = \frac{193.084}{0.394} = 490.06 > f \text{ (significant)}$$

To conclude, the model is representative and adequate for the assessment of traffic noise under urban conditions. 96.2% of the variation in L_{10} can be explained by variation in the traffic speed and composition, distance of farside and nearside facades and distance from various kinds of junctions.

7.3.2.2 Effect of speed

The model indicates that with an increased speed (V) of traffic flow from 24 km/h to 48 km/h and keeping all other variables constant, L_{10} levels would be decreased by 1.7 dB(A).

7.3.2.3 Effect of junction distance

It was found that noise levels L_{10} were decreased by 2.6 dB(A) by increasing the distance from the junction from 10m to 250m and keeping all other parameters of the model constant.

7.3.2.4 Effect of traffic composition

The model shows that there are three classes of vehicles make up noise from non-free flowing traffic in urban situations. L_{10} values are increased with increasing values of these three classes.

In order to compensate between light, medium and heavy vehicles in urban traffic, M and H were multiplied by coefficient 6 and 10 respectively (Section 6.5). All these factors contribute towards the indication of differences in the generated noise level between each vehicle category.

7.3.2.5 Effect of building facade distance

L_{10} levels decreased by 1.2 dB(A) when the distance between the kerbside and nearest building facade was increased from 10 to 20 m, with all other factors constant. In connection with farside facade the decrease was 1.6 dB(A) for the same increase.

7.4 PREDICTION MODEL FOR ROAD TRANSPORT NOISE (L_{10}) IN SUBURBAN AND URBAN AREAS (SUBURBAN AND URBAN MODEL)

The reliability of traffic noise prediction depends on the method used and how and under what circumstances it is practised. Thus, it is necessary for practical reason to derive a model for the precise prediction of road traffic and noise under different conditions such as suburban areas of 64 km/h speed limit.

A practical and comprehensive model has been introduced for suburban and urban environments. All the data from 204 suburban and urban sites were employed in the computation by using the NFNOS computer program. The final reliable formula was:

$$L_{10} = 58.6 - 5.99 \log_{10}V + 11.4 \log_{10}Q + 0.183P$$
$$-5.94 \log_{10}F - 0.0102\ J - 2.46 \log_{10} N \qquad \ldots (7.2)$$

where:

Q = Traffic flow (v/h)

N = The distance between measurement point and nearside building facade, (N=d-k) (m)

P = Percentage of medium and heavy vehicles (%)

This model is simple, practical and accurate. The coefficient of correlation was increased significantly when traffic flow and percentage of medium and heavy vehicles were included unlike the 'Urban Model' which was based on traffic composition.

The 'Urban and Suburban model' is usually necessary when the speed of considered traffic ranges from 10 to 75 km/h. In some sites the speed was found to reach 57 km/h in typical urban situations and 75 km/h in suburban in spite of the speed limit of 48 and 64 km/h in urban and suburban areas respectively. The model also provides an alternative tool based on necessary parameters such as Q and P. Figure 6.5 shows a simplified flow chart of the above model using the NFNOS program (Section 6.2). See also Appendix B.

Based on the results obtained, the urban and suburban model gives a significant relationship between noise level and the independent variables as follows:

(1) Significant correlation coefficient, R=0.969 (The critical value of R= < 138 at the 0.05 level of significance and R= < 0.181 at the 0.01 level). The standard deviation of L_{10} about the regression line was 0.770 dB(A).

(2) Based on a residual analysis, E=± 1.8 dB(A) for 99% of sites, the model is adequate.

(3) Employing the confidence interval estimate, the true slope is estimated with 99% confidence to be between +1.05 and +0.954. These values are clearly above zero. Thus, there is a significant positive relationship between measured L_{10} values and L_{10} values predicted by the urban and suburban model with 99% confidence. Figure 7.4 illustrates measured noise levels versus noise levels calculated by the urban and suburban model.

(4) A test of a null hypothesis was also employed to check the significance of the model by comparing VR with f-distribution on appropriate df (See Table 7.7). The model proved significant.

$$VR = \frac{304.57}{0.614} = 496.04 => f(6,197)_{0.1\%} = 4.04$$

(5) Each independent variable makes a significant contribution to the model in the presence of the other variables. The contribution is obvious in the following analysis of variance.

Predictor	df	SS	MS
$log_{10}V$	1	245.655	245.655
$log_{10}Q$	1	1082.375	1082.375
P	1	76.959	76.959
$log_{10}F$	1	321.334	321.334
J	1	47.595	47.595
$log_{10}N$	1	53.504	53.504
residual	197	121.015	0.614

$$MS = \frac{SS}{df}$$

$$f(1,197)_{0.1\%} = < 11.38$$

VR = > f in all cases (significant)

(6) The use of the variables which were not considered by previous practice (Chapter 4) has caused a significant improvement to the model fit. For example, the employment of V, J and F has increased the R^2 from 62.25% to 93.8% as follows.

Source	df	SS	MS	$R^2\%$
regression 1 ($\log_{10}Q, P, \log_{10}N$)	3	1212.838	404.3	62.25
regression 2 ($\log_{10}V, J, \log_{10}F$)	3	614.585	204.9	31.55
regression 3 (1 and 2)	6	1827.423	304.57	93.8
residual (1 and 2)	197	121.015	0.614	

$$MS = \frac{SS}{df}$$

$$f(3,197)_{0.1\%} = < 5.8$$

$$\text{VR(regression 2)} = \frac{204.9}{0.614} = 333.7 > 5.8 \text{ (significant)}$$

To summarise, the model is accurate, representative and adequate for the assessment of traffic noise level associated with urban and suburban conditions. 93.8% of the variation in L_{10} can be explained by variation in the traffic speed and flow, percentage of medium and heavy vehicles, distance of farside and nearside building facades and distance from various junctions.

7.5 PREDICTION MODELS FOR ROAD TRANSPORT NOISE (L_{eq}) IN BUILT-UP AREAS

The equivalent sound level (L_{eq}) is recommended by ISO and it has been found favourable in Europe (Louden, 1985), but as yet it has not been widely used in Britain for traffic noise measurements (see Section 4.3.2).

This section aims to develop comprehensive methods to assess and predict noise (L_{eq}) from interrupted traffic in urban and suburban areas as well as to test the validity of L_{eq} dB(A) in British conditions.

For practical design purposes three models were established for determining traffic noise levels in terms of different factors and circumstances. They are based on the same previously mentioned 204 sites. The models were developed utilising the same previous measurements and analysis procedures. They may be classified as follows:

7.5.1 Urban Prediction Model:

Examination of L_{eq} dB(A) in terms of the independent variables showed that the best model to fit the data from the 172 urban locations was:

$$L_{eq} = 54.9 - 6.11 \log_{10}V - 5.51 \log_{10}F - 0.0104\ J + 11.70 \log_{10}(L + 6M + 10H) - 4.01 \log_{10}(d - k) \quad \dots (7.3)$$

This model was originally developed in terms of W instead of F. Modification to the above form, like the L_{10} model, also increased the accuracy of prediction as well as the reliability of the model. The model gave a good correlation coefficient, R = 0.974, standard deviation = 0.734 and accuracy of prediction with ±2.2 dB(A). Table 7.1 illustrates a comparison of the above model with a similar L_{10} model (Eq. 7.1). This model provides slightly less accurate results than those obtained from the L_{10} model. However, in spite of this disadvantage there is a significant correlation (see Table 7.7). Also, the model includes the most significant design parameters and is a practical method for use in urban planning and environmental assessment. Fig 7.6 shows measured L_{eq} versus L_{eq} calculated by the model.

Coefficient	Component	Prediction Model	
		L_{10}	L_{eq}
a_0	constant	+57.0	+54.9
a_1	$\log_{10}$V	-5.60	-6.11
a_2	$\log_{10}$F	-5.39	-5.51
a_3	J	-0.0108	-0.0104
a_4	$\log_{10}$(L+6M+10H)	+11.70	+11.70
a_5	$\log_{10}$(d-k)	-4.00	-4.01

Table 7.1 Comparison between the coefficients of L_{10} and L_{eq} Urban Models, 172 positions (Equations 7.1 and 7.3)

7.5.2 Suburban and Urban Prediction Model:

It was decided to devise another prediction model for different conditions and design parameters. Thus, 204 suburban and urban sites were studied. The model, which was found to correlate well with the data, is as follows:

$$L_{eq} = 56.5 - 6.53 \log_{10}V + 11.6 \log_{10}Q + 0.172 P - 6.48 \log_{10}F - 0.0098 J - 2.47 \log_{10}N \quad ... (7.4)$$

The model showed a high correlation, R = 0.960, st. dev. = 0.864 and accuracy within ±2.5 dB(A). Table 7.2 shows a comparison of the above model with a similar L_{10} method (Eq.7.2). Again the model proves a little less accurate than the L_{10} model. In spite of this disadvantage there is a significant interaction (see Table 7.7). This model is also comprehensive and provides the planner with another tool based on fundamental parameters. Fig 7.7 shows measured L_{eq} versus L_{eq} calculated by Eq. 7.4. Also, a clear relationship between measured L_{10} and measured L_{eq} was obtained and is presented in Figure 7.8.

Coefficient	Component	Prediction Model	
		L_{10} dB(A)	L_{eq} dB(A)
a_0	constant	+58.6	+56.5
a_1	$\log_{10}$V	-5.99	-6.53
a_2	$\log_{10}$Q	+11.4	+11.6
a_3	P	+0.183	+0.172
a_4	$\log_{10}$F	-5.94	-6.48
a_5	J	-0.0102	-0.0098
a_6	$\log_{10}$N	-2.46	-2.47

Table 7.2 Comparison between the coefficients of L_{10} and L_{eq} Suburban & Urban Models, 204 positions (Equations 7.2 and 7.4).

7.5.3 Relationship between L_{eq} and L_{10}, L_{50}, L_{90}:

In Britain the following relationship was determined for noise from freely flowing traffic (Robinson, 1969):

$$L_{eq} = L_{50} + \frac{(L_{10} - L_{90})^2}{56} \qquad \text{... (7.5)}$$

where the value of the constant term depends upon the traffic conditions.

Of course, the structure of this model is dependent on the method used and the circumstances of the freely flowing traffic. Also, the value of the constant should be re-examined especially when the noise level generated by non-free flowing traffic is considered.

The values of L_{10}, L_{50} and L_{90} and L_{eq} have already been obtained from the analysis of the data at 204 sites. Thus, Eq. 7.5 has been further developed, using the NFNOS Computer Program in order to find the best formula for noise from an interrupted flow situation. The best formula was found in the following structure:

$$L_{eq} = 0.968\, L_{50} + 0.436\, (L_{10} - L_{90}) \qquad \text{... (7.6)}$$

where 0.968 and 0.436 are empirical constants.

The model shows accuracy with ± 2.4 dB(A), R = 0.974 and st.dev. = 0.723. It is clear that there is significant correlation (see Table 7.7). Fig 7.9 illustrates measured L_{eq} versus L_{eq} calculated by Eq. 7.6.

7.6 RELIABILITY OF PRESENT NOISE PREDICTION METHODS

Many prediction models for traffic noise have now been utilised in developed countries. Unfortunately, non-free flowing traffic models have not been yet formalised properly and the available methods have several disadvantages (Chapter 4). Therefore, this work will only be compared to those previously defined methods to which it is clearly related, to assess the obtained models.

A direct comparison between the existing prediction methods is a rather difficult thing to achieve because of the differences in methodology and conditions between the surveys. However, the Department of The Environment (1975) method was tested. The measured data from forty sites were examined by it. It was found that the differences between measured and predicted values ranged between +2 and +7 dB(A). The DOE method proved unsuitable for the prediction of noise from non-free flowing traffic. This conclusion was anticipated since the DOE method is based on the conditions of freely flowing traffic, as mentioned in Chapter 4.

The data were also put into the Sydney (Burgess, 1977) and Ontario (Hajek, 1975) methods which have been described in Chapter 4. The output shows that the Ontario method is inaccurate for non-free flowing situations. It gave low correlation coefficient, R=0.20. This is a natural result since the Ontario method was originally based on free flowing traffic specifications, see Figure 7.10.

The Sydney method gave a little higher correlation coefficient R=0.73 but a low level of accuracy. This was also expected because the Sydney method was developed only in terms of free flowing conditions in urban areas, see Figure 7.11.

The more closely related prediction methods are TRRL which was issued by Gilbert *etal*. (1980) and BRS which was based on research by Fisk et al. (1974). Both of these methods were evaluated for the purpose of comparison and are described in Chapter 4. The readings taken at the 172 urban sites were put into the TRRL formula to compare the output with the result of the 'Urban Model', while the data of 204 positions were put in BRS method to assess the result of the 'Suburban and Urban Model'.

The conclusions of the comparison are reported in Table 7.3 which shows the difference between measured and predicted values (Residual), standard deviation and correlation coefficient. The results presented in the table indicate that the TRRL method provides reasonable correlation of L_{10} levels in contrast with previous methods. The table also shows the higher level of correlation of the Bath models compared with the methods defined above. It is clear also that close agreement was obtained between the measured and predicted values.

Figures 7.12 and 7.13 show measured noise levels L_{10} plotted against values predicted by the TRRL and BRS models. These again reflect the reliability of the Bath models compared with existing methods. The main reasons probably are that TRRL and BRS ignored a number of traffic and other urban and suburban related variables. These are the speed of vehicles, the presence of junctions and the influence of the farside building facade. Furthermore, they are based on a small amount of field work which certainly does not adequately represent actual environmental noise, as it exists in daily life. However, it is hoped that this research contributes to a greater understanding of the problems of road transport noise in built-up contexts.

Method	Index dB(A)	Residual (E) measured-predicted	St.dev.	R
TRRL (172 sites)	L_{10}	±3 for 89% of the cases	2.23	0.75
BATH (172 urban sites)	L_{10}	±1.3 for 99% of the cases	0.62	0.981
BRS (204 sites)	L_{10}	±3 for 87% of the cases	2.27	0.70
SYDNEY (204 sites)	L_{10}	±3 for 88% of the cases	2.13	0.73
ONTARIO (204 sites)	L_{10}	±5 for 77% of the cases	3.05	0.20
BATH (urban and suburban 204 sites)	L_{10}	±1.8 for 99% of the cases	0.77	0.969

Table 7.3 Comparison of Bath models with existing methods

7.7 BUILDINGS AND TRAFFIC NOISE PROPAGATION

Road traffic is usually approximated by an acoustic line source positioned above the road. Thus, attempts have been made to predict urban noise levels in terms of source characteristics and propagation path. The attempts have been restricted by propagation methods and the multiplicity of source-types in built-up situations. None of these has found its way into common application(Lyon, 1974).

The comprehensive prediction model in urban and suburban contexts must be able, firstly, to assess the traffic noise level in terms of its functions, and secondly, to evaluate the influence of the surrounding characteristics on the propagated noise. Both of these have been taken into account by this study.

This section aims to examine further the influence of surrounding building structures on the level of noise in order to test the validity of the developed models. The following subsections discuss the effect of shielding and the height of the buildings.

7.7.1 Shielding by adjacent buildings

It has been seen in Section 3.3.4 that the presence of buildings in urban and suburban contexts increases the level of propagated noise. The facade of buildings on each side of the road network can cause several multiple reflection paths between source and receiver. The amount of reflection usually depends on the absorption coefficient size and nature of the reflecting walls as well as road and traffic parameters. The distance from the source to the reflecting surface and the distance from the surface to the receiver also play a significant part.

The difference between the total level of propagated noise outside the buildings and the level of transmitted noise inside them depend on the interaction of the above components.

In urban and suburban areas, noise barriers, as mentioned in Chapter 4 are not an appropriate method of reducing noise disturbance. Neither are limiting traffic flow or increasing the distance between buildings and the road network an easy target. Therefore, modification of the facades directly exposed to road traffic is a practical option.

The following gives the result of field measurements indoors and outdoors to evaluate the attenuation of noise level due to the walls of buildings.

7.7.1.1 The sites

Sites were chosen in different parts of the city, along level roads. Sites were selected where buildings flanked only part of the road length, with open areas adjacent to those buildings. The sites were chosen so that the measurements could be made at the same distance from nearside kerb for open and shielded locations. This was necessary so that simultaneous measurements could be carried out, associated with the same conditions, e.g. traffic flow. The difference between measured noise level in open and shielded sites reflected the amount of abatement in the level of noise due to the walls of buildings.

In view of the difficulty of finding such locations, only three pairs of sites were studied as follows:

(1) Kingsmead House (site no.IE): a tall modern building with eight floors (including ground floor). The building is located near a traffic light intersection and facing Charles Street which carries two-way traffic on four lanes. It lies in a typical office area, while the condition of traffic is medium. The distance between the nearside kerb and building facade

was 2.8m. On each floor, there are rooms which face the street with small windows.

The existence of an open area adjacent to this building and alongside the same street provided the opportunity for simultaneous measurements indoors and outdoors (site no.2E).

(2) Riverside building (site no.3E): an three-storey building situated 1.5m from the Lower Bristol Road. On each floor of the building large windows face the road.

Again, the availability of adjacent open land provided the opportunity to study the noise attenuation due to the shielding(site no.4E)

(3) A building in London Road (site no.5E): an old two-storey building. The building lies alongside London Road where the traffic is heavy. Large window exists on the ground floor,while the upper part contains small ones. An open area exists beside the building (site no.6E). The distance from nearside kerb was 3.5 m.

7.7.1.2 Results

The measurements were carried out for six hours simultaneously at each pair of sites (open and shielded). These were between 10.00 and 12.00 midday and 15.00 and 17.00 hours. The variables of interest were recorded simultaneously. It was decided to carry out simultaneous measurements outdoors and indoors. The distance between the measurement point and the nearside kerb was roughly the same for each measurement,inside the building and in the open. The distance between the microphones was as small as possible.

Table 7.4 shows a comparison between shielded and unshielded positions. The abatement in L_{10} values were from 10.4 to 16.4 dB(A). The result reflects the importance of effective shielding provided by buildings in built-up situations. It was found that the exposed facade plays a major part in contrast with the rear and side facades. The effects of distance were also evident, e.g., sites 5E and 6E. Wide windows and whether they were open or closed, also effected the level of indoor noise.

Table 7.5 shows a comparison between measured and predicted L_{10} values for open and shielded sites, using the Bath Urban Prediction Model which proved its validity again. In this limited practical study a considerable reduction in the noise levels was noticed. Therefore, insulation of exposed facades may be a suitable method to protect inhabitants in highly populated centres.

	L_{10} dB(A)		
Site no.	shielded	unshielded	attenuation
1E & 2E	61.2	77.6	16.4
3E 7 4E	67.3	79.8	12.5
5E & 6E	69.6	80.0	10.4

Table 7.4 Comparison between shielded & unshielded positions

Site no.	measured L_{10} dB(A)	predicted L_{10} dBA( )	residual dB(A)	condition
1E	61.2	62.3	-1.10	shielded
2E	77.6	79.1	-1.50	unshielded
3E	67.3	66.7	0.60	shielded
4E	79.8	78.9	0.90	unshielded
5E	69.6	69.1	0.50	shielded
6E	81.0	80.1	0.90	unshielded

Table 7.5 Comparison between measured & predicted L_{10} values of open & shielded sites, using Bath urban model (Equation 7.1)

7.7.2 Height of buildings

Previous practice shows that when the height of the flanking facade is greater than or comparable with the street width, there is a build-up of reverberation in the street which can be calculated by totalling the various multiple reflection propagation paths involved (Wiener, Malme and Gogos, 1965). Scant literature is available concerning the relationship between the indoor noise level and height of buildings.

The following involves simultaneous measurements of the characteristics of indoor noise levels, on each floor of high-rise buildings, and on the ground floor.

7.7.2.1 The sites

The selected site was number 1E. It was decided to carry out simultaneous measurements on the ground floor and each floor inside the buildings just behind the exposed facade. The level of noise in dB(A) was calculated in each case.

7.7.2.2 Discussion

Table 7.6 illustrates indoor noise level associated with the height of building.

The table indicates that noise levels do not vary much with the height for the first three floors. But on the fourth floor, the level of noise was higher by 1.2 dB(A) than on the ground floor. This is probably because of the effect of reflection. The top floor showed a significant reduction in the level of noise (2.4 dB(A)).

This result means that only the top of high-rise buildings is exposed to less noise. In low-rise buildings no change in the level was found (site 3E also gave the same conclusion).

When the windows were open, noise level values were found to increase by 1dB(A) on the 8th floor, and by 12dB(A) on the lower floors.

The 'Urban Model' (Eq.7.1), also gave a high level of accuracy, ± 1.6 dB(A), when the measured and predicted values were compared.

In summary, it can be said that noise levels in built-up situation do not vary with elevation for low-rise buildings, while the decrease is obvious at the top of high-rise buildings. For planning and design purposes, therefore, attention must be directed towards the insulation of the exposed walls and windows, since the majority of buildings are low-rise.

Floor no.	Indoor noise level dB(A)	Measurement no.
1	63.5	1
2	63.0	
1	63.4	2
3	64.0	
1	63.0	3
4	63.0	
1	63.8	4
5	65.0	
1	62.8	5
6	60.9	
1	61.4	6
7	59.2	
1	58.0	7
8	55.6	

Table 7.6 Variation of noise level, L_{10}, with elevation above the ground (simultaneous measurements at ground floor and each floor of high-rise building, closed windows). 1=Ground floor

Model No.	conditions	f-distribution (0.1%)	VR
7.1	urban (L_{10})	<4.42	843.23
7.2	urban and suburban (L_{10})	<4.04	496.04
7.3	urban (L_{eq})	<4.42	618.74
7.4	urban and suburban (L_{eq})	<4.04	409.12
7.5	L_{eq}, L_{10} L_{50}, L_{90}	<7.32	567.43
7.7	urban (L_{50})	<4.42	222.36
7.8	urban (L_{90})	4.42	82.77
7.9	urban and suburban (L_{50})	<4.04	214.09
7.10	urban and suburban (L_{90})	<4.04	86.39

Table 7.7 Test of significant of overall prediction models
(The models are significant since VR>f)

7.8 L_{50} AND L_{90} MODELS

Analysis of data has facilitated the evaluation of other noise indices, such as L_{50}, L_{90} as a function of independent variables.

The following formula were established for urban area conditions:

$$L_{50} = 40.9 - 3.9 \log_{10}V - 6.04 \log_{10}F - 0.0146\ J + 13.1 \log_{10}(L + 6M + 10H) - 3.86 \log_{10}(d - k) \qquad \text{... (7.7)}$$

where:

R = 0.900

st. dev. = 1.32

Residual = ±3 for 95% of situations.

Fig 7.14 shows measured L_{50} noise levels versus levels calculated by above model.

$$L_{90} = 29.2 - 2.64 \log_{10}V - 7.00 \log_{10}F - 0.0165J + 14.4 \log_{10}(L + 6M + 10H) - 3.6 \log_{10}(d - k) \qquad \text{... (7.8)}$$

where:

R = 0.845

st. dev. = 2.30

Residual = ±3 for 90% of situations.

Fig 7.15 shows measured L_{90} values versus values calculated by the above model.

For urban and suburban conditions, the following equations summarise the findings:

$$L_{50} = 46.7 - 4.39 \log_{10}V + 12.9 \log_{10}Q + 0.188 P - 6.89 \log_{10}F - 0.0131 J - 2.81 \log_{10}N \qquad \ldots (7.9)$$

where:

R = 0.90

st. dev. = 1.30

Residual = ±3 for 95% of cases

$$L_{90} = 35.8 - 3.20 \log_{10} V + 14.3 \log_{10}Q + 0.188 P - 7.98 \log_{10}F - 0.0147 J - 3.12 \log_{10}N \qquad \ldots (7.10)$$

where:

R = 0.850

st. dev. = 2.20

Residual = ±4 for 94% of cases

L_{50} and L_{90} show much less interaction with independent variables in contrast with L_{10} and L_{eq}. However, they provide useful information about the performance of noise levels under interrupted flow conditions, see Figures 7.16 & 7.17. The relationship between measured and predicted noise climate is shown in Figure 6.18.

7.9 ADVANTAGE OF THE DEVELOPED PREDICTION MODELS

The developed L_{10} and L_{eq} dB(A) prediction models have the following advantages:

(1) They are practical means in order to save time and money and avoid the need for field measurement.

(2) They are simple and easy to understand by city engineers who may have a limited knowledge of acoustics but are in a position to consider traffic noise.

(3) They use variables that are necessary for design and planning purposes.

(4) They covered the limitation aspects of previous practice. Also, they are based on real field data and considered areas of differing land use under various sets of urban and suburban conditions.

(5) They were designed, using the multiple regression analysis method, to bear some relation to former practice, in order to obtain meaningful conclusions.

(6) They provide rapid prediction to an accuracy appropriate to the planning process.

(7) They rely on existing transportation engineering standards.

(8) The components of the models showed a good level of correlation with human responses (next Chapter).

7.10 SUMMARY

This chapter described the development, accuracy, reliability and advantage of new noise prediction methods. They were an empirical methods based on 2448 thirty-minute noise level measurements taken at 204 urban and suburban locations.

This study considered the relationship between noise levels and individual variables as coupled variables (Chapters 4 and 5), but only a low degree of interaction was obtained. This is because the variables are closely interrelated in a built-up environment. When all the selected variables were employed, it was found that the correlation coefficient increased significantly.

Therefore, evaluation of noise level as a function of all the variables combined, under various conditions as described in this chapter, was found the best means of prediction. The proposed methods enable planners and designers to make a good and quick evaluation of the noise level, when the traffic is subject to stop and go conditions. Two kinds of prediction models were produced as follows:

(1) Urban Models: these models (equations 7.1 and 7.3) predict the values of L_{10} and L_{eq} in terms of traffic composition and speed, presence of various junctions and locations of buildings facades. The models are suitable for urban conditions where speeds below 48 km/h and traffic composition, i.e, 3 classes of vehicles, affect the environment significantly.

(2) Suburban and urban models: these predict L_{10} and L_{eq} (equations 7.2 and 7.4) in connection with speed, traffic flow, percentage of medium and heavy vehicles, presence of various junctions and location of farside and nearside building facades. The models are for conditions when speed is between 10 and 75 km/h and Q is significant. They also provide an alternative means of prediction.

The developed L_{10} and L_{eq} models have been compared with existing methods, i.e, Sydney, Ontario, TRRL and BRS and have shown superiority. They predicted L_{10} and L_{eq} with a high level of accuracy under a wide range of conditions. The effects of shielding and elevations of buildings were also reported. Insulation of exposed facades was found to be a suitable method to protect inhabitants in built-up areas. Internal noise levels do not vary with elevation of low-rise buildings, while the decrease is obvious at the top of high rise buildings.

Models for the prediction of L_{50} and L_{90} were developed but gave low levels of accuracy.

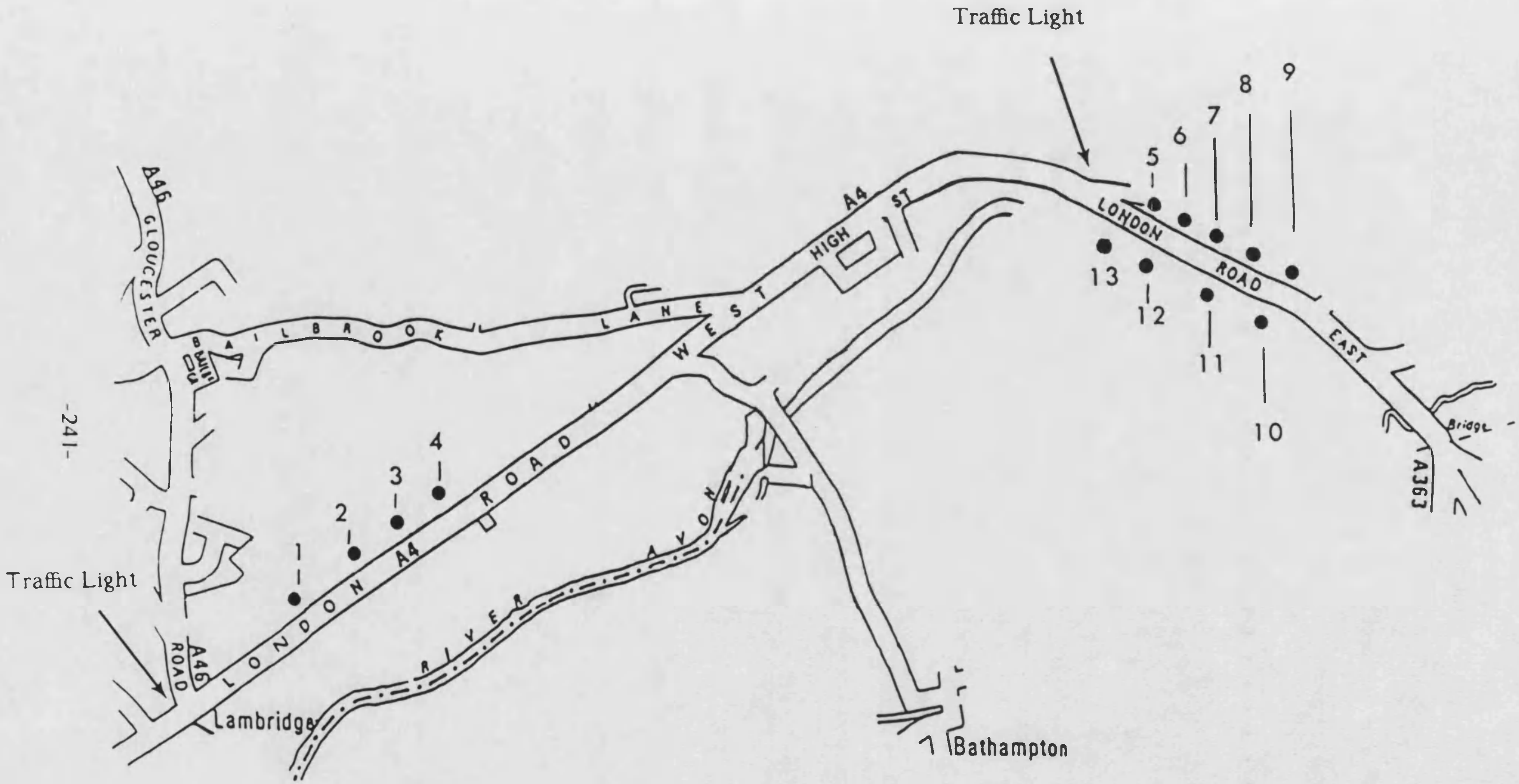


Fig 7.1 Distribution of suburban area sites - London Road

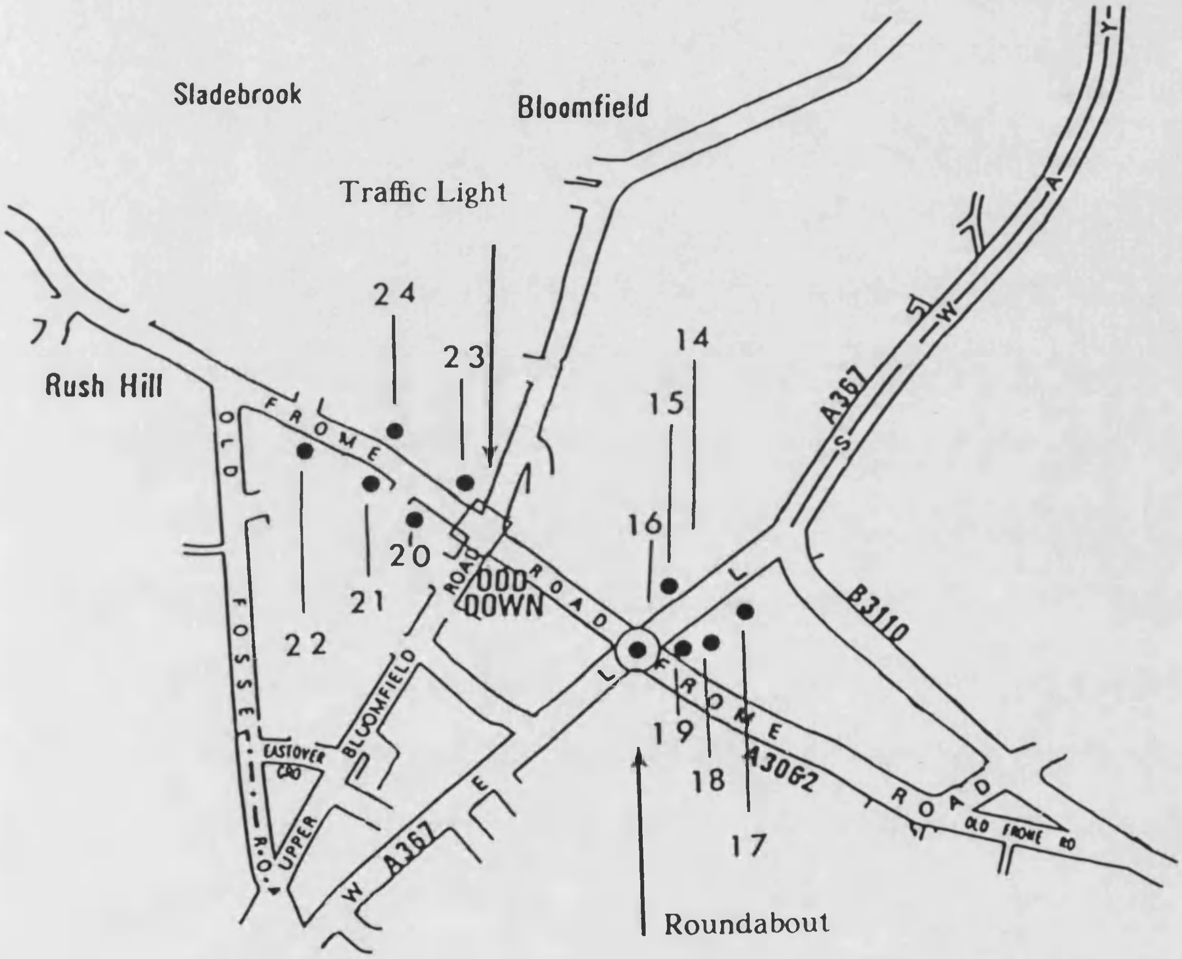


Fig 7.2 Distribution of suburban area sites - Wells way

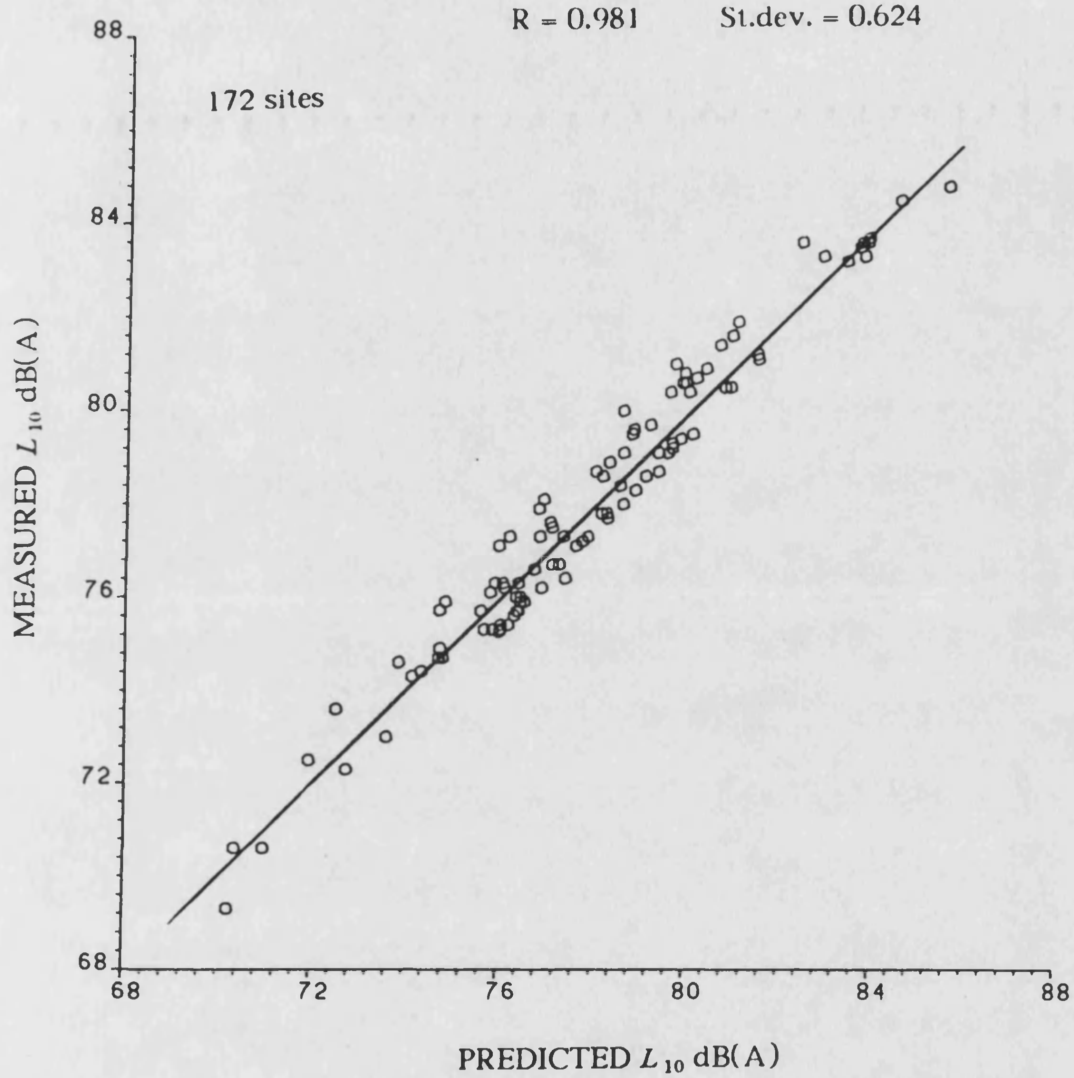


Fig 7.3 Measured L_{10} versus L_{10} predicted by Bath urban conditions model (Equation 7.1)

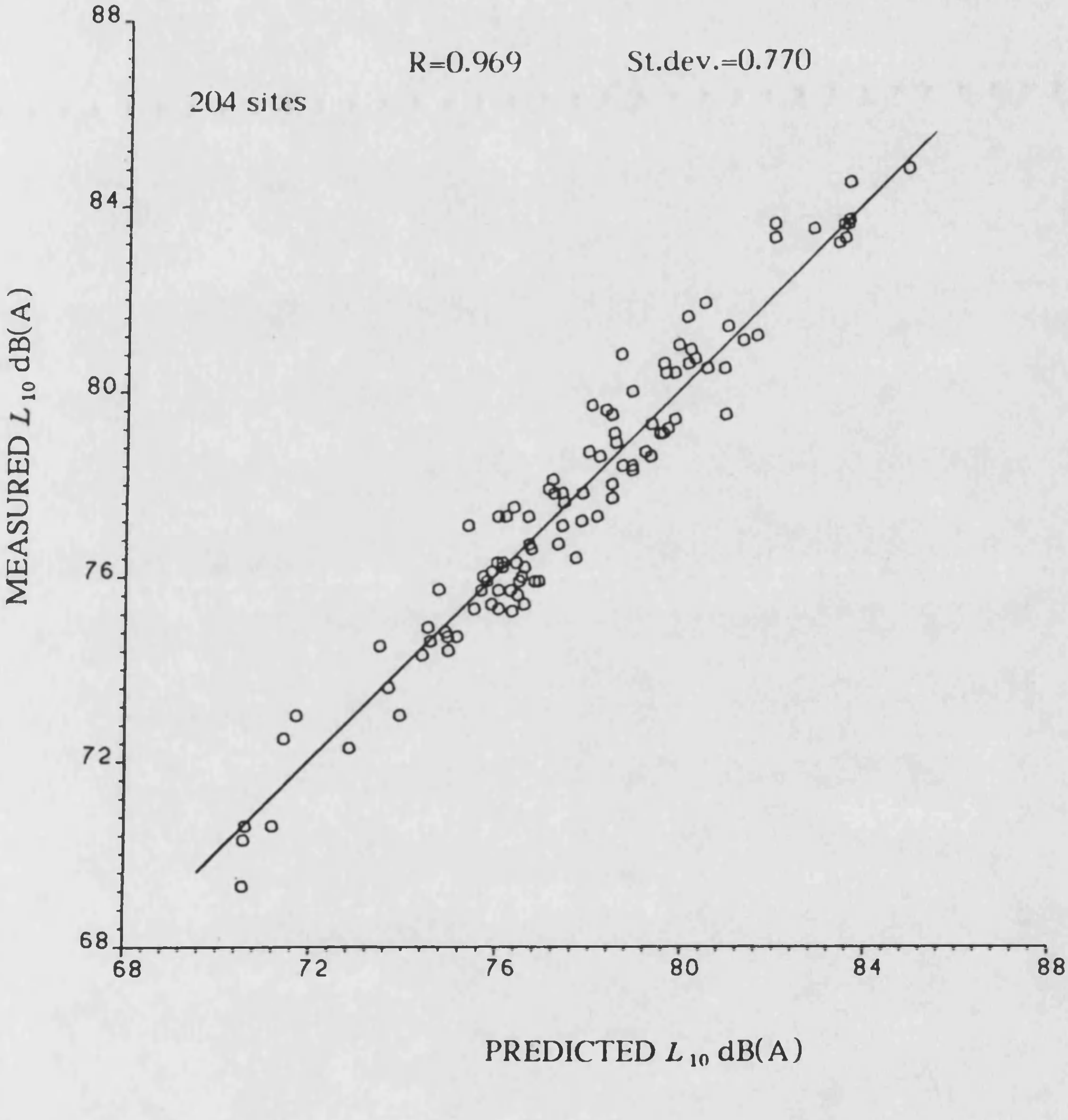
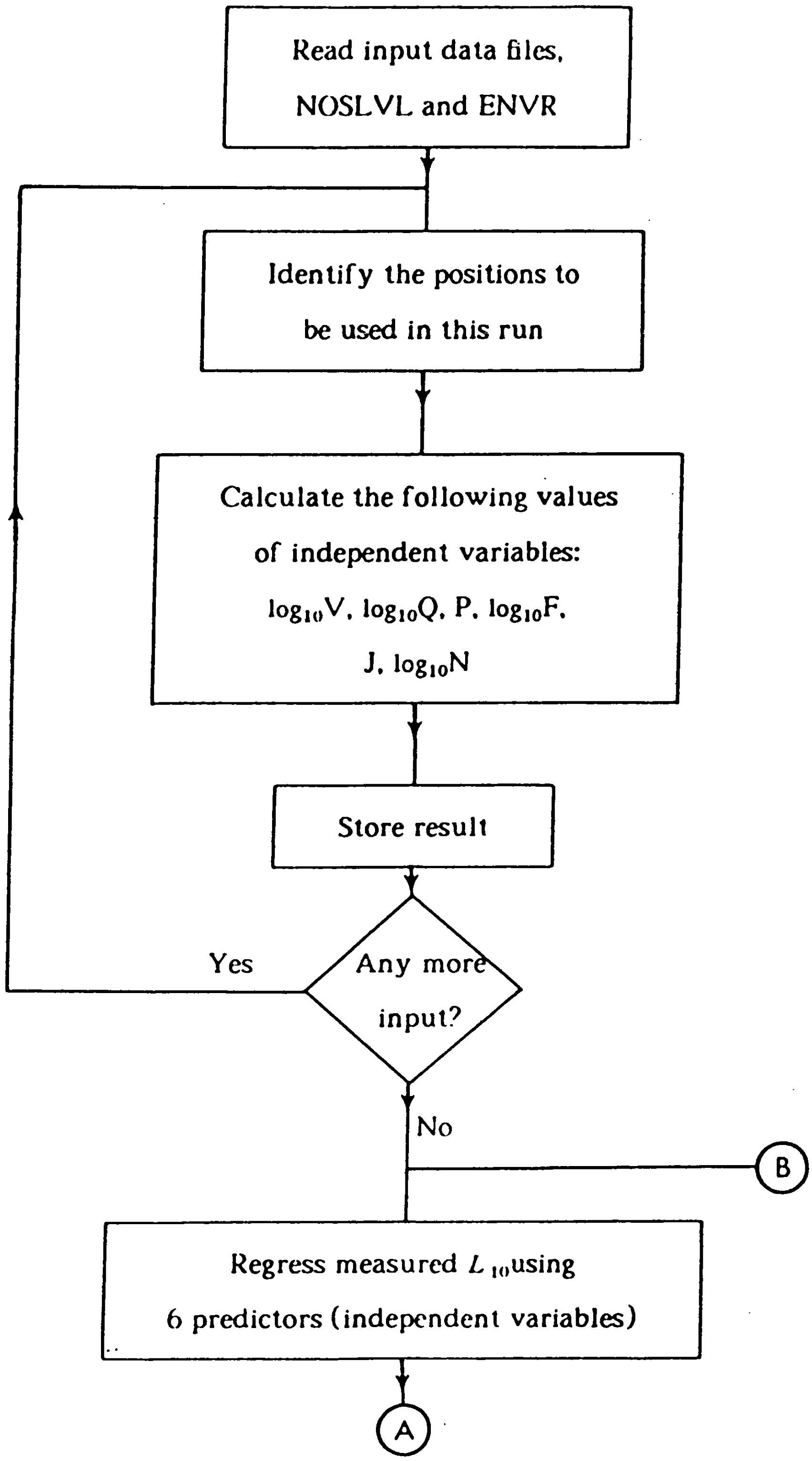


Fig 7.4 Measured L_{10} versus L_{10} predicted by Bath urban and suburban conditions model (Equation 7.2)



Read input data files, NOSLVL and ENVR
Identify the positions to be used in this run
Calculate the following values of independent variables: $\log_{10}V$, $\log_{10}Q$, P, $\log_{10}F$, J, $\log_{10}N$
Store result
Any more input?
Yes
No
B
Regress measured L_{10} using 6 predictors (independent variables)
A

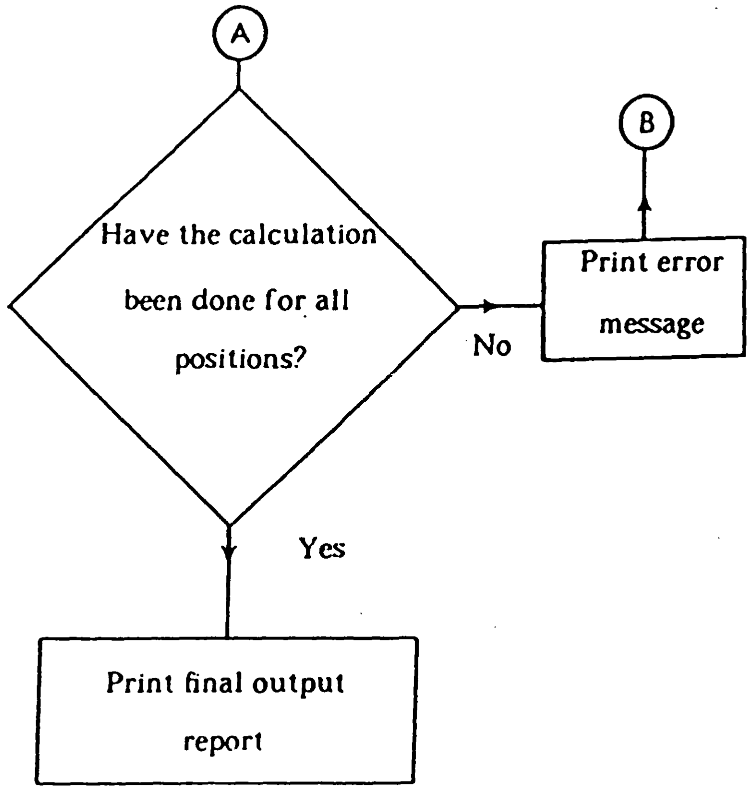


Fig 7.5 Simplified flow chart of urban and suburban conditions model using UFNOS program

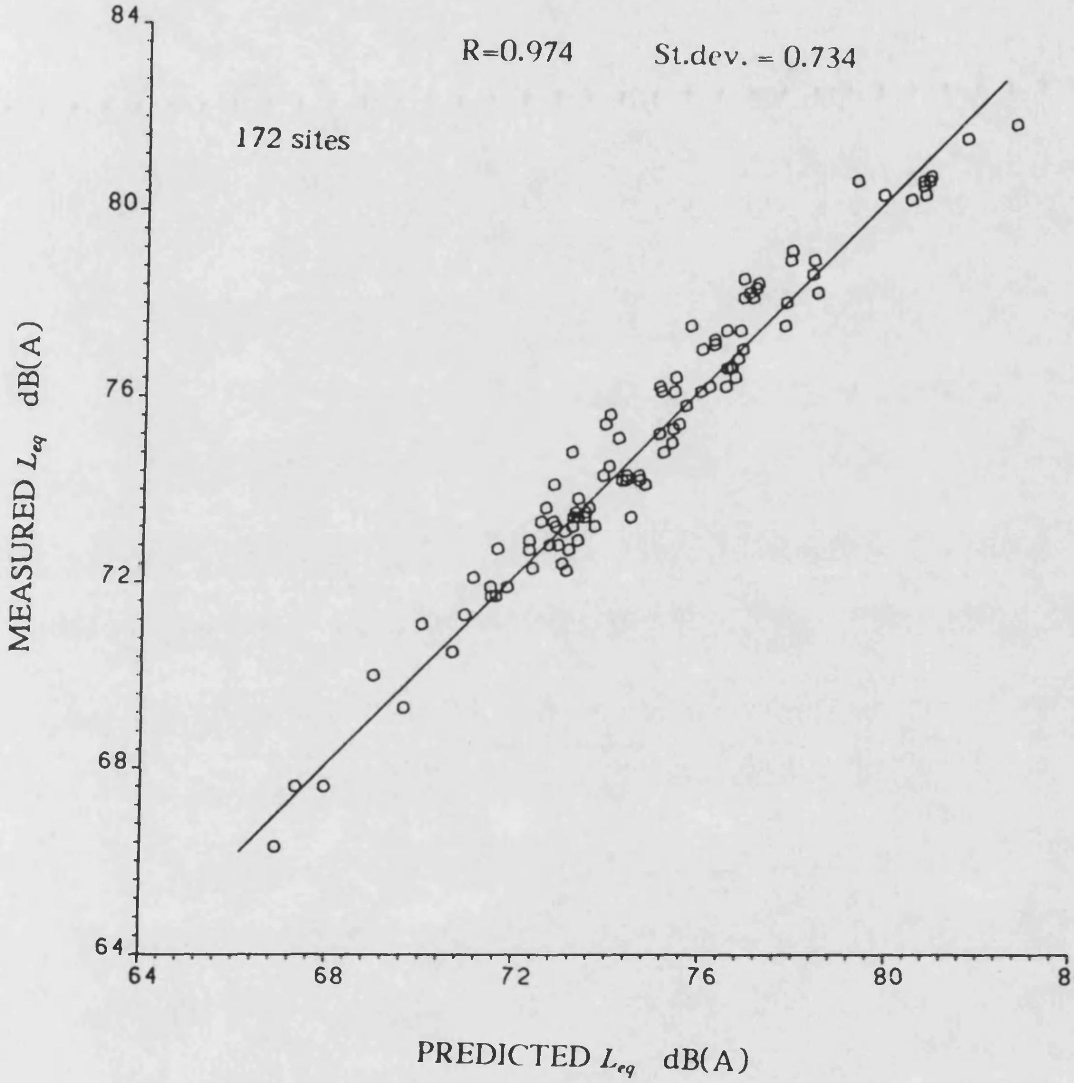


Fig 7.6 Measured L_{eq} versus L_{eq} predicted by Bath urban conditions model (Equation 7.3)

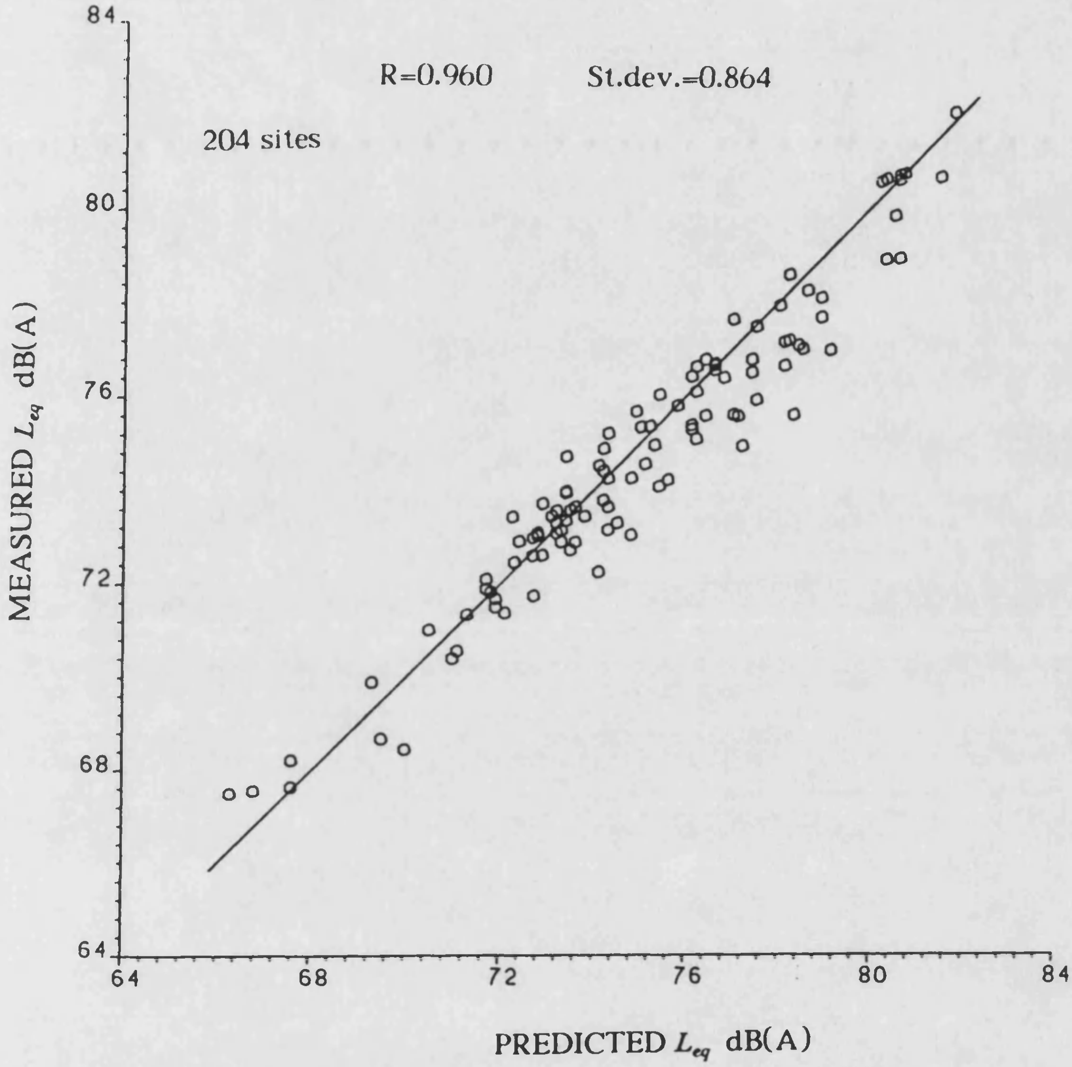


Fig 7.7 Measured L_{eq} versus L_{eq} predicted by Bath urban & suburban conditions model (Equation 7.4)

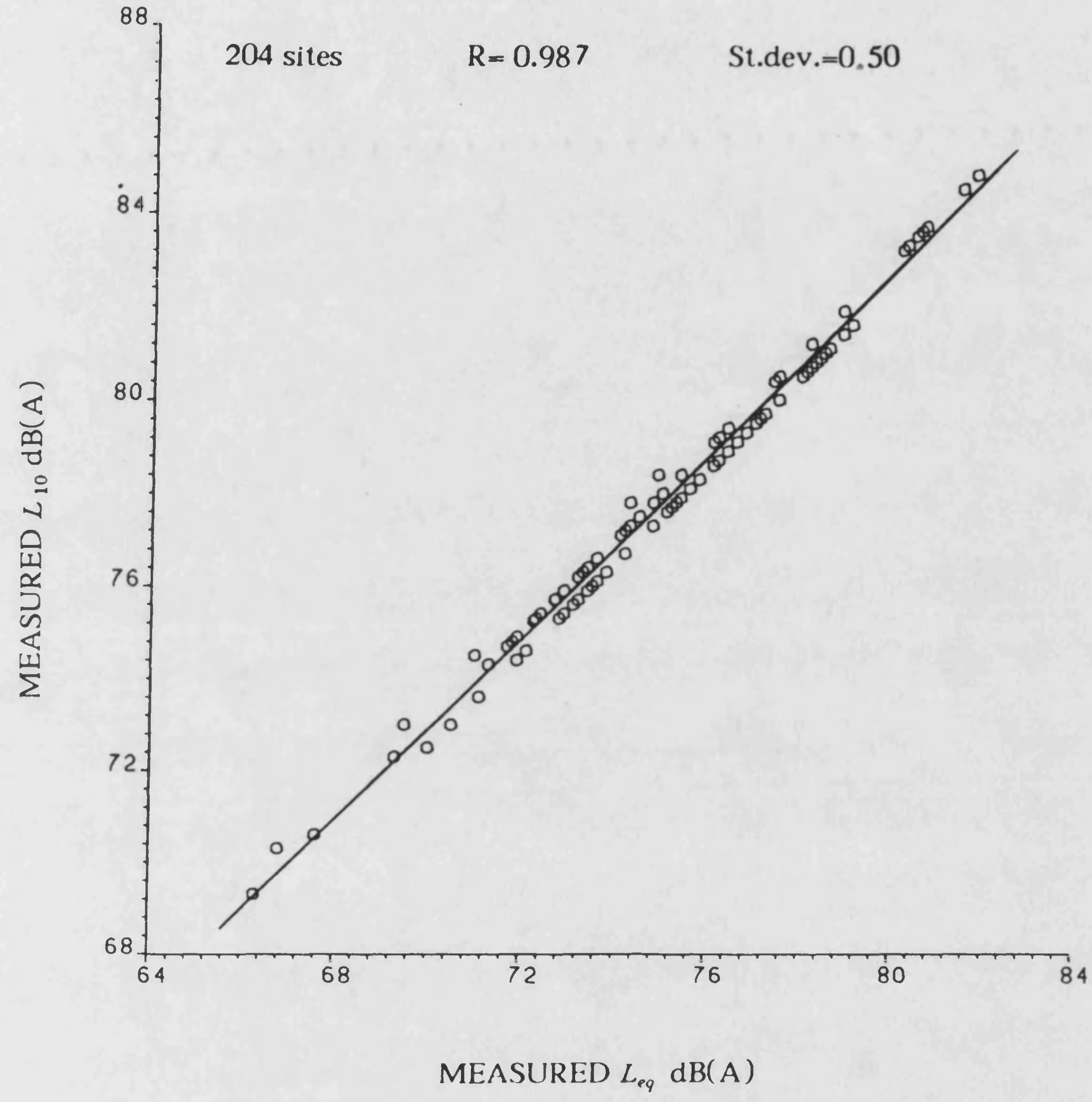


Fig 7.8 Measured L_{10} versus measured L_{eq} for urban and suburban conditions

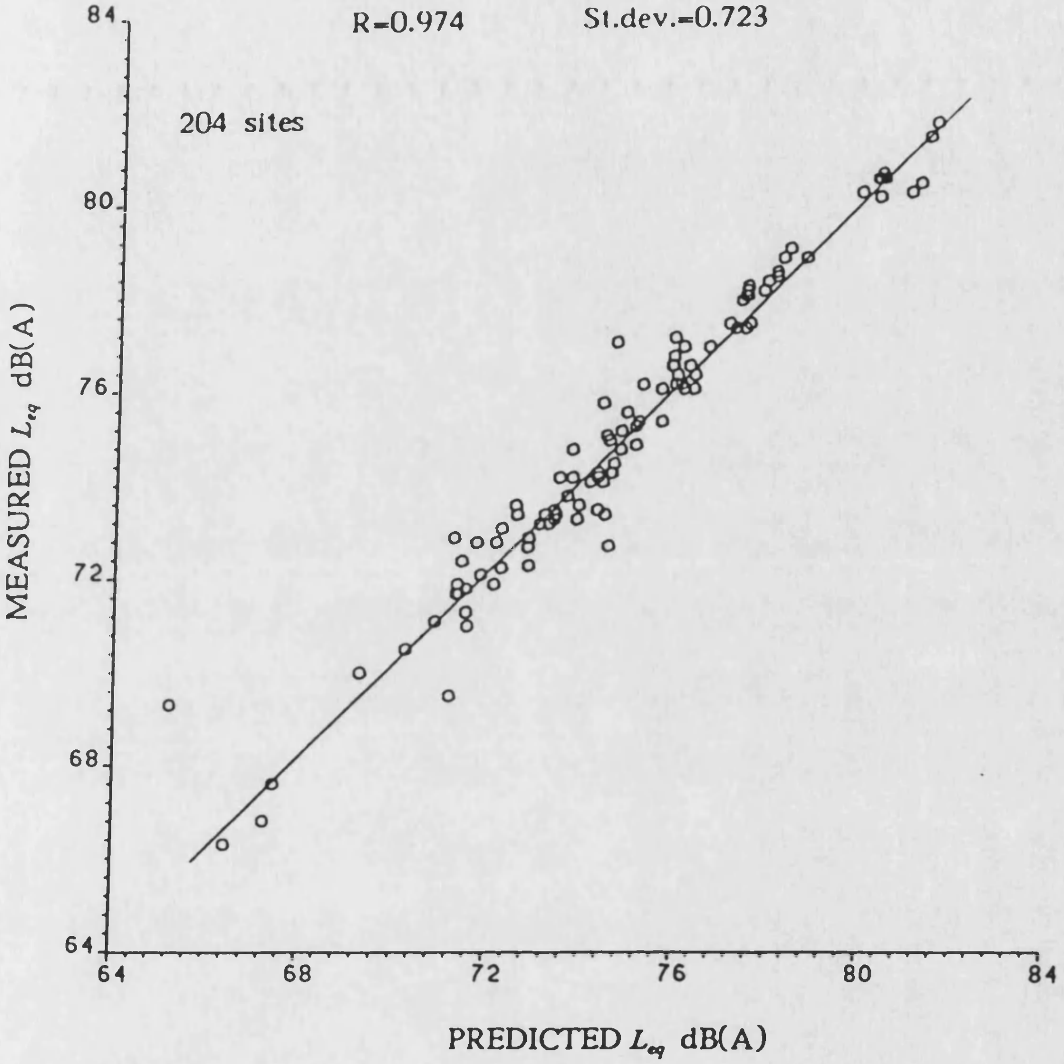


Fig 7.9 Measured L_{eq} versus L_{eq} predicted by

Equation $(L_{eq} = 0.968\ L_{50} + 0.436(L_{10} - L_{90}))$

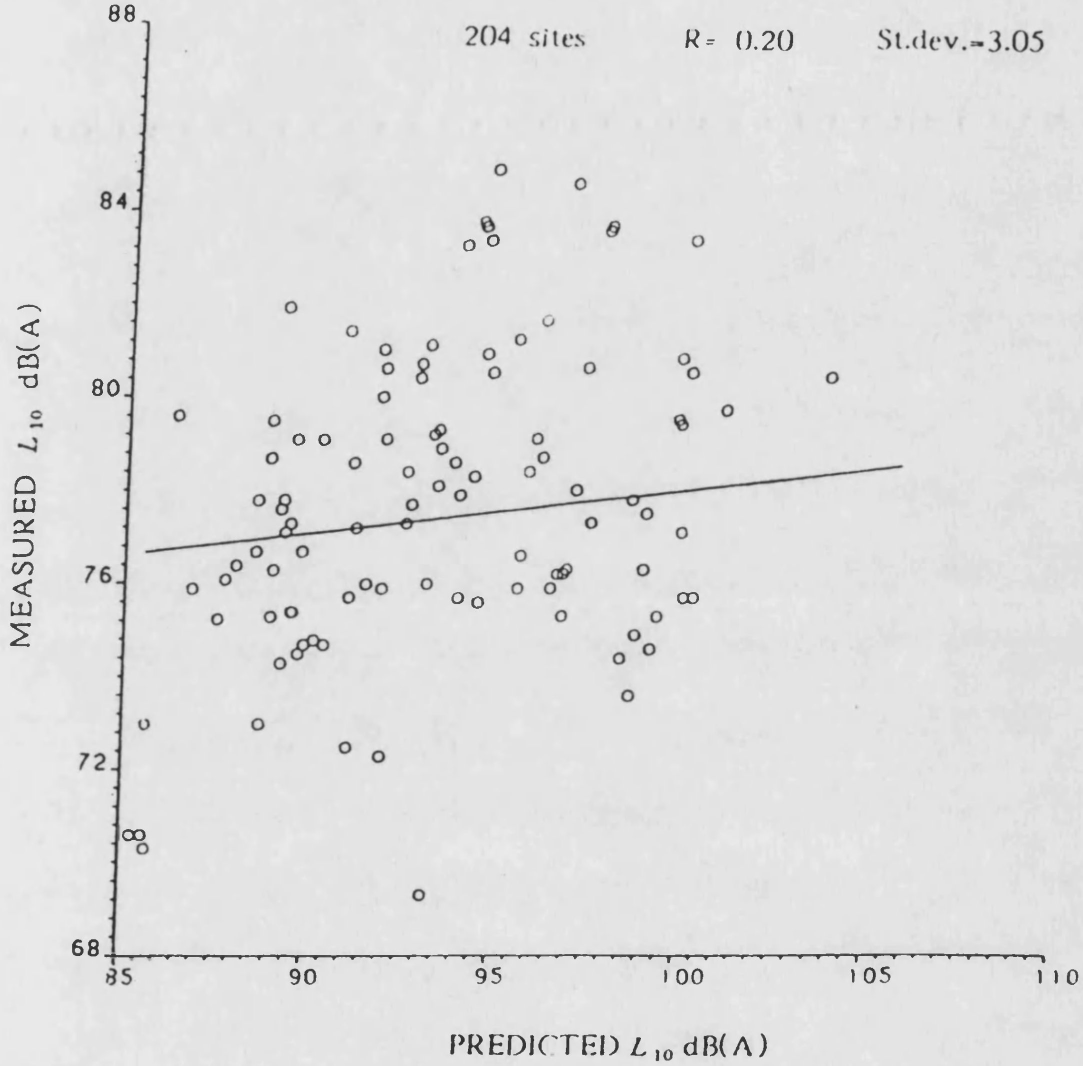


Fig 7.10 Measured L_{10} versus L_{10} predicted by Ontario model (Equation 4.12)

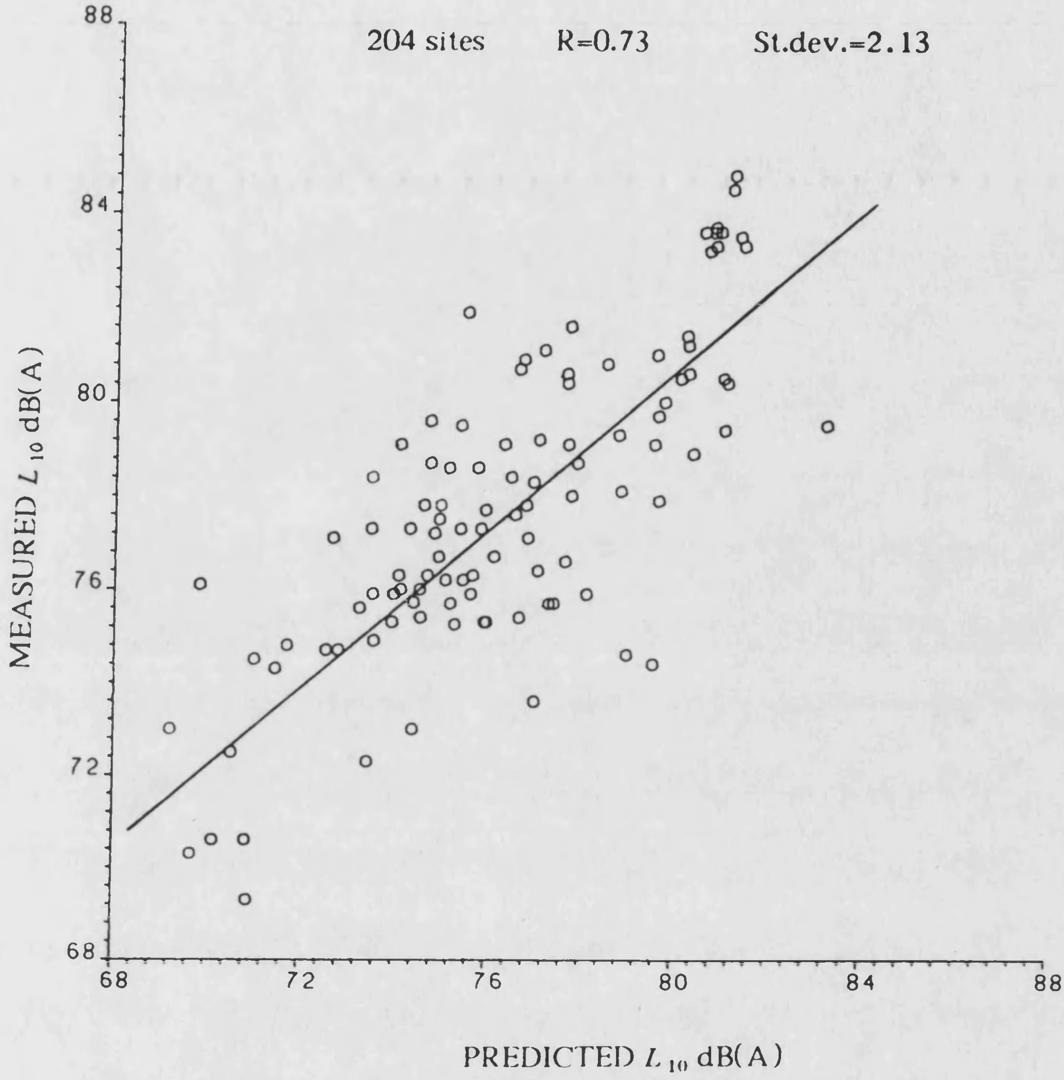


Fig 7.11 Measured L_{10} versus L_{10} predicted by Sydney model (Equation 4.15)

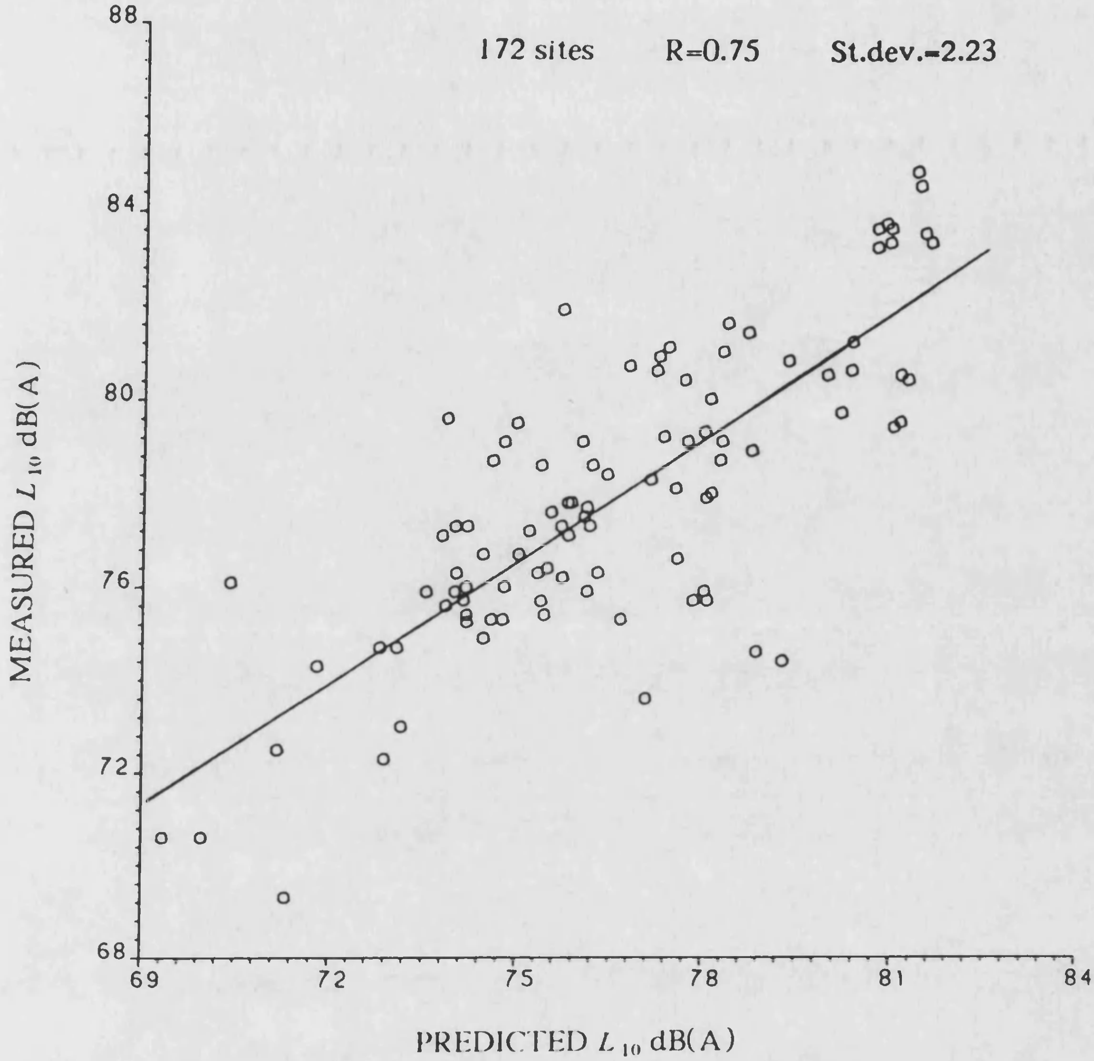


Fig 7.12 Measured L_{10} versus L_{10} predicted by TRRL model (Equation 4.19)

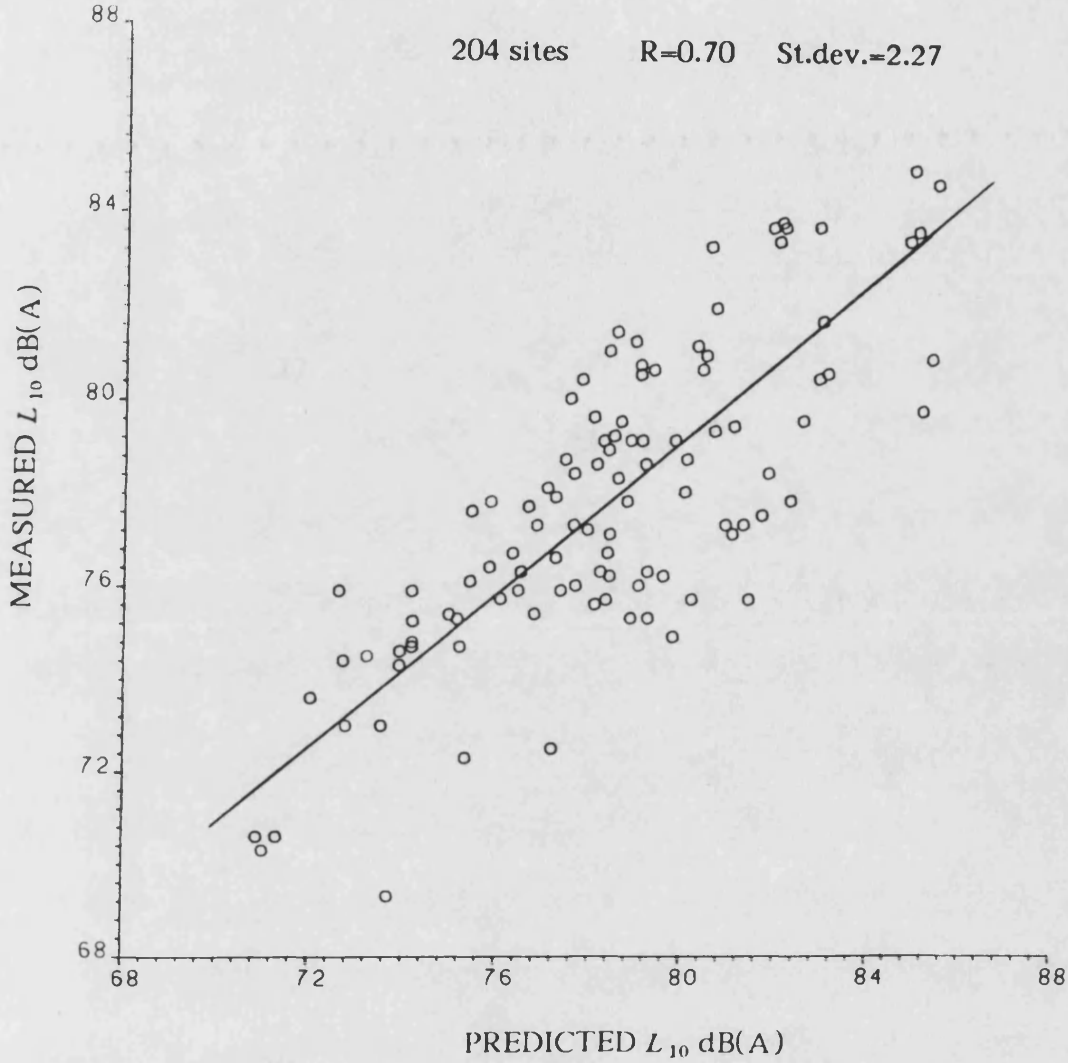


Fig 7.13 Measured L_{10} versus L_{10} predicted by BRS model (Equation 4.17)

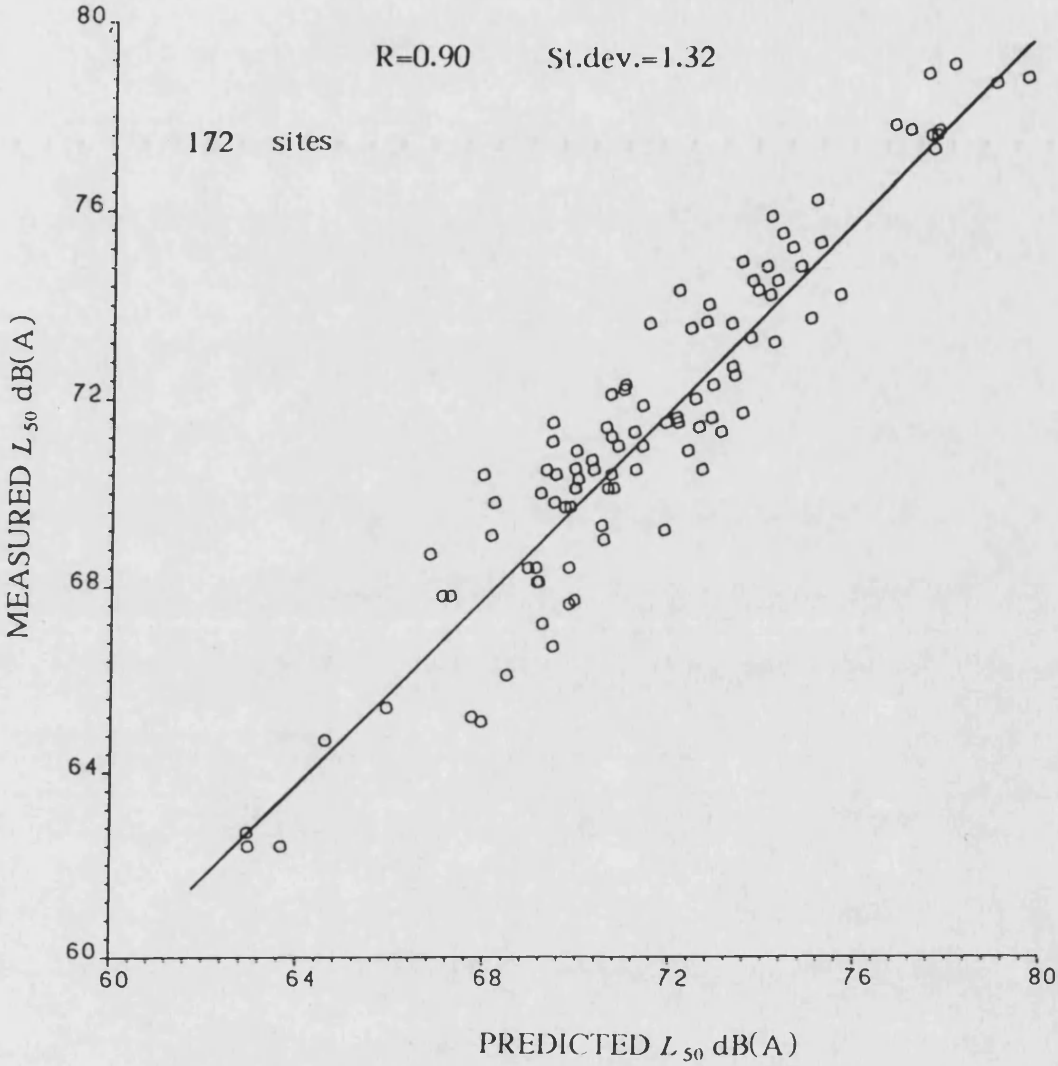


Fig 7.14 Measured L_{50} versus L_{50} predicted by Bath urban conditions model (Equation 7.7)

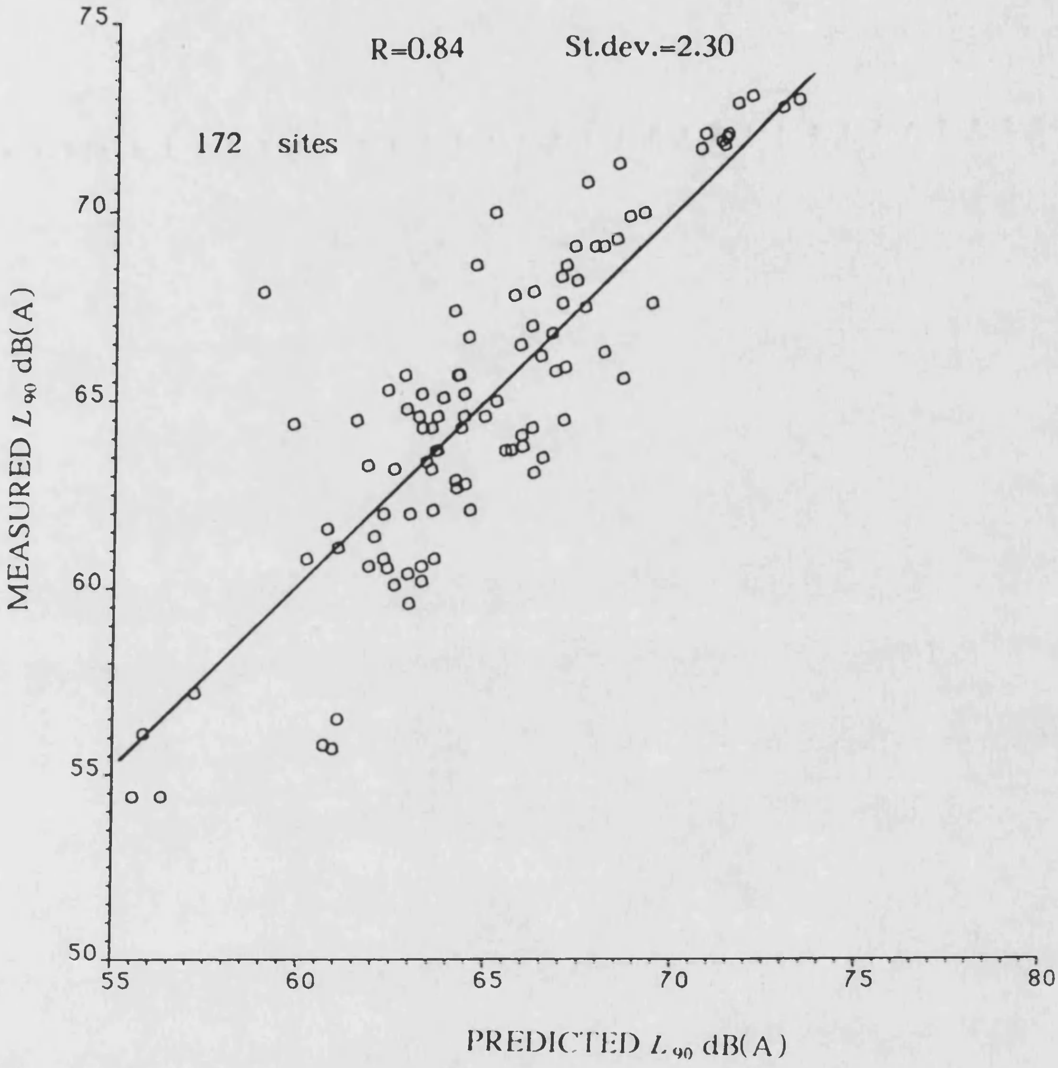


Fig 7.15 Measured L_{90} versus L_{90} calculated by Bath urban conditions model (Equation 7.8)

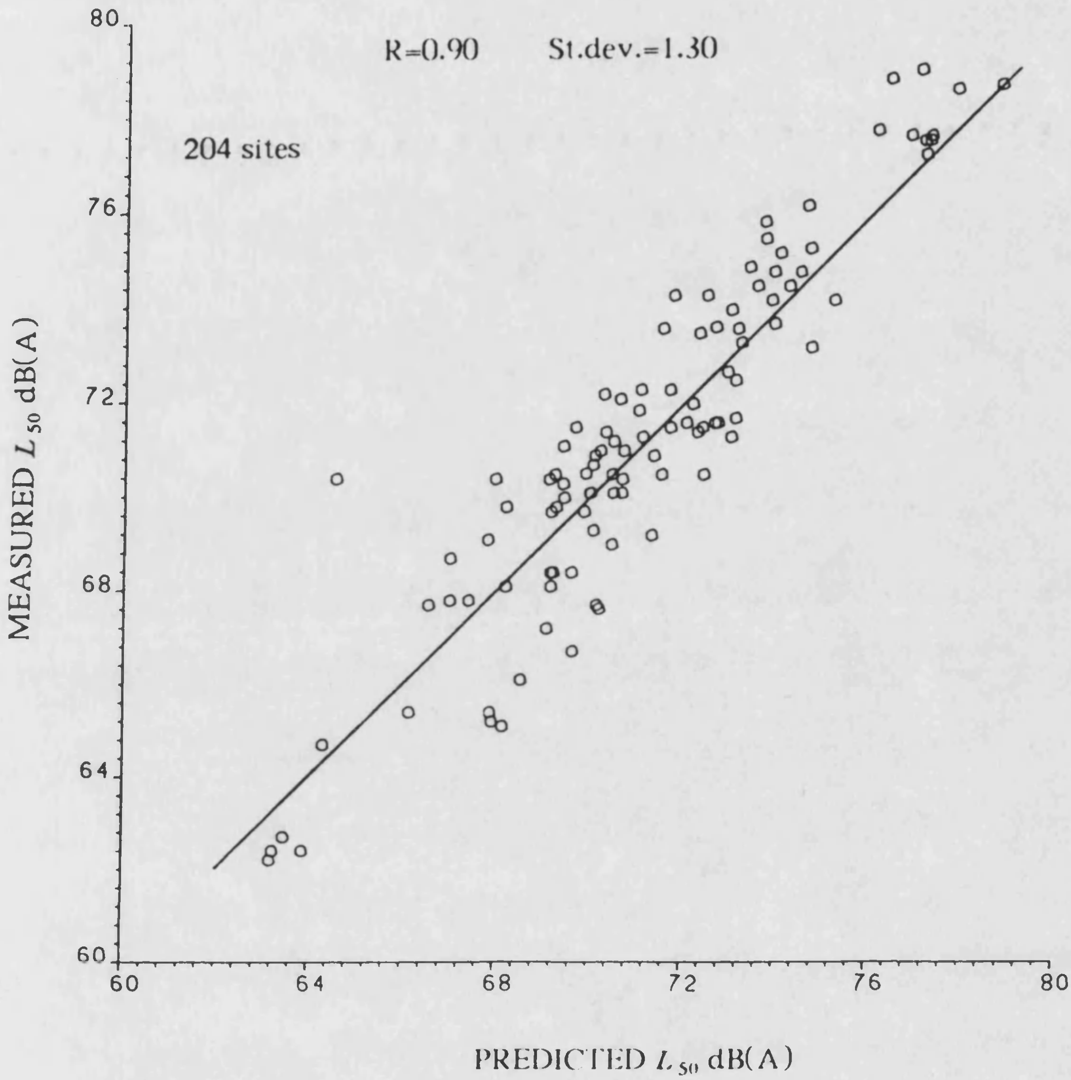


Fig 7.16 Measured L_{50} versus L_{50} predicted by Bath urban & suburban conditions model (Equation 7.9)

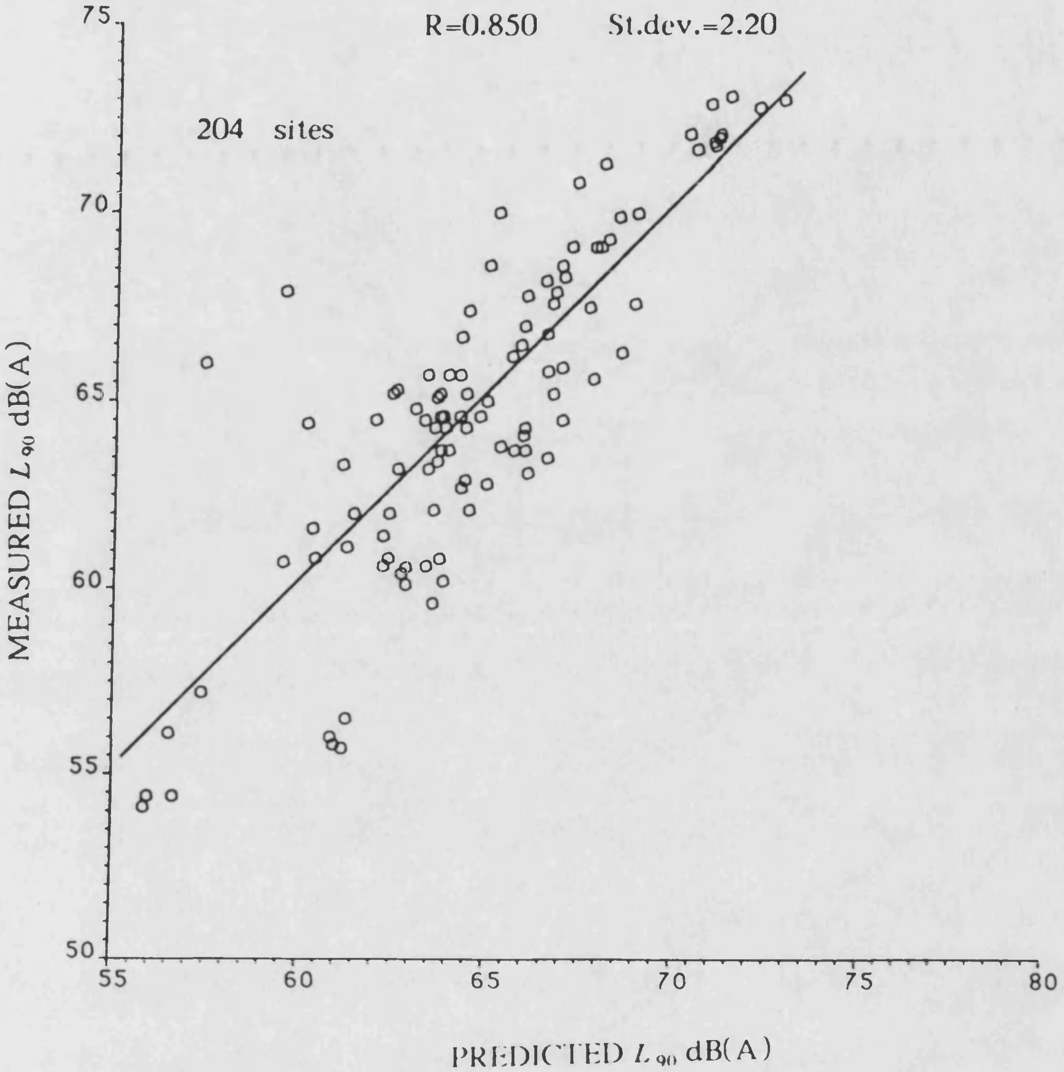


Fig 7.17 Measured L_{90} versus L_{90} predicted by Bath urban & suburban conditions model (Equation 7.10)

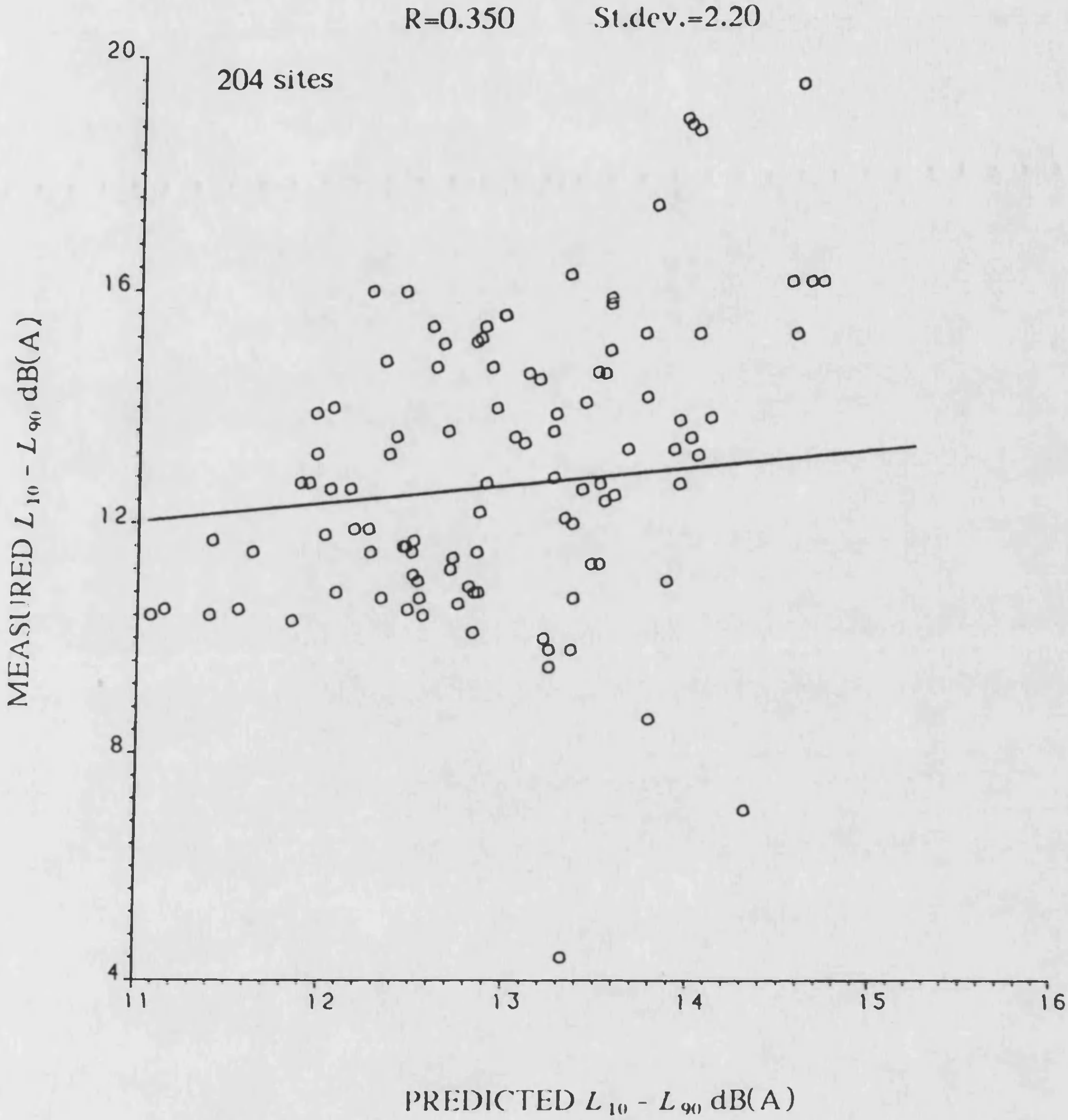


Fig 7.18 Measured noise climate versus noise climate predicted under urban & suburban conditions.

CHAPTER EIGHT

SOCIAL RESPONSE TO NOISE FROM INTERRUPTED TRAFFIC FLOW

8.1 INTRODUCTION

In order for traffic noise control to be feasible, information from three main areas needs to be considered. The first of these is individual vehicle noise (see Chapter 2). The second is road traffic noise (see Chapters 3 to 7). The third is the effect of traffic noise on people, with which this chapter deals.

The function relating noise exposure and the reaction of the public is usually termed the dose/response relationship. It is important to study this kind of relationship firstly, in order to estimate the extent of noise problems according to people's judgements, and secondly, to develop standards for planning and design objectives.

The influence of noise exposure on a population is often assessed by determining the presence of annoyance. This has been defined as being a feeling of displeasure which the human knows or believes could adversely affect his health or well being (Borsky, 1972).

It is well known that in real life, human response to noise varies not only with physical quantities of noise, but also with many other contributing factors, some of them have been discussed in aforementioned chapters. An example of these factors are traffic characteristics of the area, physical and emotional sensitivity level, and susceptibility of the individual (Croome, 1977). Thus, many researchers have proposed various scales for evaluating the effects of noise. But the complexity of people's response to noise encountered in daily life, especially in urban and suburban contexts, is responsible for the lack of availability of a standard evaluating system which can be widely applied.

In this chapter the results of a social survey, which was carried out by means of an appropriate questionnaire, are shown. This survey was carried out in order to complete a wide-ranging study on noise from restricted traffic flow in built-up areas (Previous chapters). The objectives were firstly, to evaluate the extent of noise problems. Secondly, to validate existing noise indices in order to define the best annoyance predictors. Thirdly, to examine the relationships between built-up area features and people's responses. Fourthly, to evaluate the findings of the physical measurements taken in this study. Fifthly, to model the dose/response relationship.

The chapter is subdivided into parts as follows:

(1) Measuring people's response to environmental parameters
(2) Previous surveys of subjective response to traffic noise
(3) Selection of area and social survey sample
(4) The questionnaire structure
(5) Pilot study
(6) Analysis of questionnaire responses - Stage One of Analysis
(7) Dose/response relationship - Stage Two of Analysis

8.2 MEASURING PEOPLE'S RESPONSE TO ENVIRONMENTAL PARAMETERS

Several studies have shown that traffic noise is a major disturbance and source of complaints in many countries (OECD, 1980). The effect of environmental noise and especially urban traffic noise on people, is evident. These effects can be classified into three main categories (OECD, 1980):

(1) The physiological damage, e.g. noise induced hearing loss.

(2) The effects on activities, e.g. interference with sleep, communications, and the effects on performance.

(3) The psychosociological effects, e.g. nervousness caused by noise.

People's reaction to noise is usually assessed using socio- acoustic studies. The socio-acoustic approach entails the use of a social survey to determine the effects of noise on inhabitants, in conjunction with noise measurements to determine the extent of their noise exposure. Data concerning the response of people to road traffic is collected by questioning a representative number of the population in the area of interest. The designing of questions, the method of interviewing and the sample of population depend on the objective of the study. But the main goal usually is to establish a relationship between the annoyance felt by people and the prevailing level of traffic noise. The results obtained vary between surveys. For example Griffiths and Langdon (1968) produced a specific noise index (Section 4.3.3). Along with subjective judgement on noise disturbance, a tiny number of previous surveys considered the interaction with other disturbing factors which characterise the urban environment such as traffic lights, intersections, roundabouts, land use, accelerating and decelerating situations.

One of the principal tasks in a social survey is the structuring of the questionnaire to be used. This depends upon whether the interview is to be unstructured or structured. In an unstructured interview, specially trained interviewers are given a brief which does not require them to ask specific questions in a predetermined way, but leaves them free to choose the order and wording of questions and to follow up interesting points as they arise. This is useful at the early stages of study but it does not give comparable conclusions between subjects. An alternative method is the group discussion where group of usually between five and ten people are asked to discuss the topics of interest under the guidance of a trained leader. In this kind of work the subjects are not asked the same questions in the same way. So the answers cannot be aggregated into percentages or other statistics. The results are, therefore, of limited value to the researcher of a specific field of study (Watkins, 1981). In a structured interview the questions are prepared in advance. Therefore, the differential in replies between subjects is minimised. This makes analysis of results easier and for this reason valuable to the researcher of specific area of a investigation (Bradley, 1977).

In connection with road traffic noise, most of the national surveys in many countries have been based on structured interviews (Brown and Law, 1978). It appears to be the most favourable means of assessing people's response in this field of study. Indeed the wide number of variables in built-up areas, and the need to concentrate on the variable of interest, gives superiority to questionnaires designed with a structured format.

The Wilson Committee (Wilson, 1963) confirmed that a numerical scale against which the intensity of people's reaction to noise is plotted, can help to analyse the data mathematically. The annoyance scale differed from study to study both in number of bands (e.g. 5 or 7 bands), responses names (e.g No.1 definitely satisfactory to definitely unsatisfactory at No.7) or included names for all responses (e.g. 1. Quiet, 2. Acceptable, 3. Noisy and 4. Extremely Noisy).

Thus there is no standard scale now in common applications. Watkins (1981) suggested that: 'because the literature does not unreservedly recommend a particular type of scale or number of categories, research should be undertaken to discover the type of scale and number of categories most suited to the assessment of subject response to the appearance of roads and landscapes'.

In socio - acoustic research, measures of reaction are based on people's ratings of the annoyance or dissatisfaction they experience because of noise.

Some researchers measure reaction in terms of mean rating (Langdon and Buller, 1977), while others apply the percentage of residents reporting a high level of annoyance (Schultz, 1982). Normally, the level of correlation between physical measurements of noise and people's reactions is the basis for the evaluation of the situation.

8.3 PREVIOUS SURVEYS OF SUBJECTIVE RESPONSES TO TRAFFIC NOISE

This section will briefly review some field surveys of subjective response to traffic noise.

A number of surveys of subjective response to road traffic have been carried out in many countries including Britain (Langdon and Buller, 1977), Canada (Bradley, 1977) and Australia (Brown and Law, 1978). Few of them have dealt comprehensively with urban traffic noise (Fidell, 1978).

The development of a relationship between feelings and numerical objective measurements is not an easy task because the terms 'annoyance' or 'disturbance' are not pure (Croome, 1977). Annoyance is not confined to noise, it does not depend just on the event of the moment, it depends on personality. There are many acoustical and non-acoustical factors that influence the relationships. Acoustical factors depend upon the sampling techniques that are used and the propagation effects between the monitor and the subject's location (Bradley, 1977). Non-acoustical factors are generally related to the subject's attitude and circumstances. For example, wives of high-salaried air pilots may welcome living near airports. Convenience of travel or schooling may make the high level of noise a secondary consideration (Croome, 1977). Schultz (1982) has claimed that when people are greatly annoyed by noise, the effects of non-acoustical variables are reduced and the correlation between noise exposure and the expressed subjective reaction is high both for individuals and for groups.

There are several units which have been developed for assessing traffic noise. It is usually concluded that for particular responses in particular situations one unit can be better than another. Thus, it is difficult to explain why, for example, some surveys show L_{50} to be the significant predictor of people's reaction whereas others find L_{10} to be more accurate. Designers cannot wait for a unified unit to be established, so various criteria have been developed which attempt to correlate subjective and objective measurements.

In addition to the annoyance type of responses, there are also behavioural effects due to the noise affecting individual's activities and behaviour. Fig 7.1 shows the interference level on some activities caused by traffic noise, based on freeway traffic noise responses in France and street traffic noise responses in Switzerland (Schultz, 1982). It is clear that interference with sleep was more pronounced than interference with conversation, particularly when the noise of the street was considered. Miller (1974) confirmed that sleep disturbance by excessive noise reduces one's feeling of well being. Vallet, Gageux, Blanchet, Favre and Labiale (1983) investigated the effects of traffic noise on sleep disturbance. The study is focussed on the response of people living near a main road. Experiments were carried out in the homes of subjects who had habitually been exposed to noise for periods of more than four years. These results highlight that both long term average and peak levels are important in assessing sleep disturbance. The level measured inside the bedroom, and the level above which sleep quality started to become impaired were 37 L_{eq} dB(A) and 45 respectively. The study has also led to the conclusion that after many years of exposure to noise, transfer to a quieter environment provokes a considerable change to better sleep for most people. In the case of traffic on motorways or urban highways the study finds that the peak levels and the mean energy level should not exceed 45 dB(A) inside the bedroom. In London, 2,933 residents at 53 sites were interviewed to obtain data with respect to sleep disturbance. Noise levels were measured at the facades of the dwellings between the hours of 22.00 and 06.00. Night noise levels ranged from 52-79 dB(A) (L_{10}). External noise was reported as the chief cause of sleep disturbance (Langdon and Buller, 1977). Fidell (1978) summarised the result of a nationwide urban noise survey, involving over 2000 respondents at 24 sites in seven American cities, as follows: firstly, exposure to noise levels of many urban environments produces widespread annoyance, speech interference and sleep interference in the American public. Secondly, noises associated with automotive sources are the most pervasive causes of noise annoyance in urban America.

In connection with social status, Bradley (1977) found that there is no difference in annoyance response between high and low socio-economic status groups with respect to regular road noise, but for motorway noise high socio-economic status groups indicate twice as much annoyance about relatively low noise levels as the low socio-economic status groups. At high noise levels, the annoyance responses of the two groups converge. Fidell (1978) found from an urban survey in America, that traffic noise affects lower socio-economic groups more than higher socio-economic groups of society.

The conclusion of the Griffiths, Langdon and Swan (1980) study was that there were no seasonal effects on traffic noise annoyance at all. People open their windows more in summer and spend more time outdoors, but their dissatisfaction remains unchanged. The Griffiths study was based on a survey carried out in London.

Schultz (1982) reviewed the results of a number of social surveys on noise annoyance from various sources. He compared the dose/response functions and concluded that there was such close agreement across sources that they could all be represented by a single curve evaluating the impact of noise on communities. However, there is some uncertainty about Schultz's claim that he considered the relationship between the 'percentage of highly annoyed' people and L_{dn} noise levels for traffic noise is the same as that for aircraft and railway noise. Kryter (1982) argues that traffic noise causes different annoyance than aircraft noise at the same exposure level. Also, there are several studies which have shown that traffic noise causes more annoyance than equivalent exposure to railway noise (Knall and Schuemer, 1983).

It can be seen from the above brief review that noise disturbance is caused by a combination of many physiological, psychological and social factors. This makes measurement of annoyance difficult to achieve. This study has attempted to correlate subjective and objective measurements based on the survey in the City of Bath.

8.4 SELECTION OF AREA AND SOCIAL SURVEY SAMPLE

The main tasks in planning the survey were:

(1) To define the boundary of the study area, taking into account various land use and conditions.
(2) To define the total population of the study area.
(3) To select a suitable sample of people to be interviewed.

The first point was executed according to the map of the city and pilot study by the author. The urban area of Bath was selected for the study. Also, another decision had to be taken concerning the number of physical measurement sites. From the 172 urban sites considered, which were discussed in Chapters Five and Six, 48 sites eventually were chosen for the purpose of the social survey. Various areas were selected as representative of the different types of land use, at sites distributed as follows:

(1) Urban main road area: in this area sixteen sites were chosen whose reference numbers were as follows: 1,3,7,8,10,11,16,17,19,22,40,45,48,53,55,171 (see Figure 6.1).

(2) Residential area: in this area sixteen sites of the following reference numbers were chosen: 93,106,107,108,109,111,120,121,143,144,145,146,155,162,163,164 (see Figure 6.1).

(3) Shopping and office areas: in these areas also sixteen sites were selected. Their reference numbers were as follows: 63,66,67, 77,79,89,91,92,95,98,100,104,114,115,124,125 (see Figure 6.1).

Social survey sites were selected on the basis that they had to be representative of the parameters of this research which was limited to noise and its contributing factors in non-free flowing traffic situations. For example, the sites had to be flanked by buildings on both sides and various types of road junctions should be included. It is obvious, therefore, that the social survey was restricted by specific requirements. Thus the study area was selected to cover as many of the relevant aspects of noise annoyance as possible.

As regards task 2, concerning total population, there was difficulty in obtaining the official figure. Thus, this task was executed according to personal communication with various experts in Avon County Council, available information in Bath Reference Library and a pilot survey.

Initially a list was prepared, including the addresses and approximate numbers of people living closest to the measurement locations on each of the 48 selected urban sites. This list totalled approximately 3340 inhabitants. Once the total number was known, the next step involved the selection of a representative sample.

Concerning Task 3, (to find a suitable sample for questioning from the 3340 individuals), a sample of 400 was finally chosen who would be individually interviewed. From these 400, 319 individuals were available for interview by the author (about 10% of the inhabitants).

Considerable effort has been put into the selection of a sample of the population to reflect the required conditions. Moreover, the establishment of a comprehensive prediction models (e.g. OTNAI in Section 8.8.3) necessitates covering a wide range of the built-up area features and this has been done (see Section 5.6.4).

There are two basic requirements for sampling procedure to fulfill. A sample must be representative, and it must be adequate (Bernson and Levine, 1983). The selected sample satisfied these requirements. It was representative since the number of people considered was restricted by the choice of specific sites. The sample was also adequate. The required sample size was also assessed by using formulas 5.1 and 5.2 (Section 5.6.4):

The adequate sample size was determined with, $e=\pm 1\%$, $p=0.5$ and 99% confidence level. It was found that the required sample size was 158 subjects out of a population of 3340, to satisfy the requirements of this study. So there is no reason why realistic results should not be obtained, since the sample eventually considered (319 subjects) was much larger than required.

The subjects had to be 18 or over and must have experienced the effect of traffic on their specific area for at least a six month period. The number of people chosen at each site varied with the total number of people available. 6 -12 subjects, therefore, were interviewed at each site. 134 subjects were interviewed in urban main road areas, 104 subjects were interviewed in residential areas, 81 subjects were interviewed in shopping and office areas. It was attempted to select people who lived as close as possible to the measurement site, in order that roughly the same level of noise should be experienced at each address.

Sites of typical non-free flowing traffic conditions were defined (48 km/h speed limit). They were alongside accelerating and decelerating streams of traffic at an appropriate distance (between 4-330m) from various junctions. The building facades flanking the roads were continuous on both sides. Light, medium and heavy traffic conditions were represented, traffic being the major source of noise at all the sites. Buildings in the study areas were chosen to be roughly of similar character, roughly of uniform appearance and close to the road. The maximum facade distance from the nearside kerb was 8m.

The environmental noise in each site was recorded on portable tape recorders for thirty minutes between 0600 and 2400 hours. Other variables were recorded simultaneously. Traffic flow ranged from 200 to 3000 v/h, while percentage of medium and heavy vehicles ranged from 0 to 20%. Road width ranged from 6 to 16m.

In the laboratory analysis, the L_{10}, L_{50}, L_{90} and L_{eq} were determined for each site. L_{10} ranged from 68.3 to 85.3 dB(A) while L_{eq} ranged from 65 to 82 dB(A). The procedures of measurement and analysis, as well as site advantages, are described in more detail in Chapter 5.

The analysis was performed by means of suitable computer programs. The SPSS and MINITAB computer systems were used. The SPSS (Statistical Package For the Social Sciences) system is a comprehensive tool for managing, analysing and displaying data. Its capabilities, for example, include input from data files, tabulation and statistical analysis. The SPSS statistical procedures provide for a wide variety of analysis such as frequency distribution, relationships between variables and correlation coefficients (see Nie, Hull, Jenkins, Steinbrenner and Bent 1975). Description of the MINITAB system has been reported in Chapter 6 (Section 6.2).

8.5 PILOT STUDY

The pilot study was performed in order to test the reliability of the questionnaire. The pilot questionnaire was designed in two parts, so that most aspects of noise annoyance and its related variables were considered. The first part of the questionnaire covered the typical three elements of noise: firstly, the source of traffic noise and its causes, for example, three classes of vehicles, existence of various junctions, accelerating of traffic and congestion of traffic. Secondly, the propagated noise levels indoors and outdoors. Thirdly, the receivers (people) who are disturbed by traffic noise, for example interference with conversation and sleep. Questions concerning the financial effect of noise and general likes and dislikes about the area were also included in this part. The second part of the questionnaire consisted of questions on general information. An example of these was classification of subjects in terms of age and sex, kind of land use and traffic flow. This part was usually filled in by the author who acted as interviewer.

The pilot study was applied at 10 sites. These sites represented the kind of situation where the main survey was to be applied, e.g. various traffic conditions, and road configurations. 72 subjects were interviewed at home, while the noise level was already obtained during the physical measurement (previous chapters).

The interviewer introduced himself in the following manner: ' I am interviewing a large number of people to find out what they think of the environmental noise from passing traffic in the area they live in '. The first seven questions refer generally to noise. So they were answered directly by the subjects. Cards showing the possible responses (e.g. a 5-point scale) were used for the rest of the questionnaire. Part Two of the questionnaire was filled immediately after leaving each subject's house.

It was noted that the people of London Road (heavy traffic conditions) reported more negative responses to traffic noise, especially heavy goods vehicles and traffic light intersections, than the people living in the residential and shopping areas (medium traffic conditions). The people in medium traffic conditions have a different attitude towards the traffic noise environment from people on main roads. It was found that the advantages and disadvantages of the public transport services, for example, can influence noise judgements. Significant correlations were obtained between people's reaction and noise levels as well as urban variables.

Examples of this were the correlation coefficients of people response for the following items: R=0.50 for outside noise, R=0.47 for indoor noise, R=0.40 for heavy lorries, R=0.70 for distance from junctions, R=0.70 for accelerating traffic and R=0.60 for sleep disturbance. The answer to the vibration question gave R=0.60 while the answers to the financial effect on the subject's property value gave R=0.50.

The people who were obviously very disturbed by the noise gave high annoyance responses to the noise related annoyance questions, for example the question of disturbance from junctions and accelerating of traffic. This was also more clearly reflected in conversation with the interviewer.

To conclude, a pilot study was carried out. It covered the various aspects of traffic noise annoyance in built-up areas. The results of the pilot study indicated that the objectives of this research could be achieved. These include the assessment, according to the people's judgement, of noise level sources and related variables, level of propagated noise indoors and outdoors and interference with normal people's activities. The pilot study also reflected the possibility of validating the findings of the physical measurements taken as part of this study (Chapters 5,6 & 7), e.g. the location of road junction was found contribute to loud noise levels during the objective and subjective investigations. The correlation coefficients obtained were significant for the majority of cases as indicated above (they were found to be higher than the critical value of R=0.232 at 0.05 level of significance). Thus, it was also possible to develop a technique for the prediction of traffic noise annoyance in terms of any of the independent variables (e.g. OTNAI which was developed from more data in Section 8.8.3). A 5-Point scale was also found convenient for the purpose of this study. This was clearly reflected in conversation with the subjects. For example, the author developed three cards showing the possible responses. The cards included a 5-point scale, a 7-point scale and a 10-point scale, ranged from definitely satisfactory at No.1 to definitely unsatisfactory at No.5, 7 and 10. The subjects described the 5-point scale as the most convenient.

As a result of the pilot study and lessons learned, the main comprehensive survey was conducted (see next section and Appendix C for the final structure of questionnaire). The main study data was analysed in two stages as follows.

8.6 STRUCTURE OF THE QUESTIONNAIRE

The questionnaire of this survey is based on principles similar to those of previous work (Langdon and Buller, 1977; Brown and Law, 1978) with several modifications and the establishment of items specific to the objectives of this study. Personal communication with some experts was also made (Sargent 1984; Vulkan 1984; Lewis 1984). The structure of the final design of the questionnaire is shown the Appendix C.

The questionnaire was designed in two parts so that most aspects of urban traffic noise annoyance were covered. The first part consisted of the following:

(i) Traffic Noise level

Question 1	- An introductory question, about the area in which subject lived to develop a sense of rapport between interviewer and subject.
Questions 2-5	- These attempted to determine the subject's general view of the area. They were predominantly concerned with the rating of the area, public service and sorts of noise. These questions were designed to identify people who were affected by other sorts of noise.
Questions 6-7	- These established the subject's attitude towards external and internal noise. They took the form of a 5 point scale.

(ii) Traffic Noise Sources

Question 8	- This was developed to indicate the class of vehicles which causes most annoyance. Vehicles were divided into: cars, vans and light goods vehicles, medium goods vehicles including buses or coaches, heavy goods vehicles and motor cycles.
Question 9	- This assessed to what extent subjects were annoyed by noise from factors such as noise from the nearest junctions, accelerating and decelerating traffic, squealing tyres and interrupted traffic.

(iii) Traffic Noise Disturbance

Questions 10-19 - These covered vibration nuisance, whether windows were open or closed, sleep disturbance, occupied parts of the building and interference with various aspects of communication, such as TV, radio, conversations and concentration.

Questions 20-21 - These dealt with the subject's specific responses to traffic noise by assessing annoyance on weekdays, at weekends and at various times during the day and night.

Question 22 - This attempted to evaluate the effects of traffic noise on the value of the subject's property. It took the form of a 5 point scale reading from not at all reduced to very much reduced.

Question 23 - This established the total number of occupants.

Question 24 - This allowed the subject to make personal comments in order to to express any feeling not mentioned in the questionnaire.

The second part of the questionnaire reported fundamental information as follows:

(i) The principal information

Questions 1-2 - These dealt with classification of subjects in terms of age and sex.

Questions 3-6 - These were concerned with land use, type of junctions and buildings, and floor number.

(ii) Variables

Question 7 - This dealt with independent variables, e.g. traffic flow.

Question 8 - This was concerned with noise levels L_{10}, L_{50}, L_{90} and L_{eq} dB(A), which were provided to compare real traffic noise level with the people's response and urban variables.

A letter of introduction and set of response cards were also provided.

8.7 ANALYSIS OF QUESTIONNAIRE RESPONSES - STAGE ONE OF ANALYSIS

8.7.1 Traffic Noise level

8.7.1.1 General

Table 8.1 gives details of the structure of the study area sample. The number of females was 156 and the number of males was 163. The result shows that the proportion of female and male samples were, roughly, equal (48.9% and 51.1%). In terms of age characteristics there was a small percentage of people over 60 (19.1%).

The 'Type of property' question shows that the buildings in study areas are mainly of a similar character. 0.9% of samples were in flats, 79.9% in terraces and 18.9% in detached or semi-detached. All the buildings had windows on the frontage facade which is a factor influencing the indoor levels to which the subject was exposed.

The percentage of subjects living at the same address for less than one year was 12.5%. It was shown that a high proportion of subjects have lived at their present address for 5-15 years. See Tables 8.2 and 8.3.

A high number of subjects experienced a noise nuisance in their area. In all locations, the predominant source of noise was road traffic noise. Noise from construction, ambulance and trains were the secondary complaints and noticed by very few subjects, Table 8.4.

Table 8.5 shows the type of junctions and predominant land use of the study area. It is obvious that 41.1% live in the main road area (heavy traffic conditions). The selected residential, office and shopping area locations were subject to medium traffic conditions mainly, and occasional heavy goods vehicles. All sites were subject to interrupted traffic flow.

SEX	Study Area % subjects	Study Area No. of subjects
Male	51.1	163
Female	48.9	156

AGE	% subjects	No.of subjects
18-39	39.8	127
40-59	41.1	131
60+	19.1	61

... contd

TYPE OF BUILDING	% subjects	No.of subjects
Flat	0.9	3
Terrace	79.9	255
Detached or Semi detached	18.9	60
Other	0.3	1

Table 8.1 Structure of study area sample -Questions 1, 2 & 5, Part 2 (319 Subjects)

YEARS	% subjects	No. of subjects
6 months, up to 12 months	12.5	40
over 1 year, up to 5 years	21.6	69
over 5 years, up to 10 years	23.2	74
over 10 years, up to 15 years	23.8	76
over 15 years	18.8	60

Table 8.2 Period of living at present address - Question 1 (319 Subjects)

FLOOR NO.	% subjects	No.of subjects
Ground	72.7	232
First	20.7	66
Second	6.6	21

Table 8.3 Floor number - Question 6, part 2 (319 Subjects)

SORT OF NOISE	% subjects	No.of subjects
Traffic noise	100	319
Ambulance	9.7	31
Fire engine	7.8	25
Train	2.8	9
Maintenance	24.8	79
People	0	0

Table 8.4 Type of noise - Question 5 (319 Subjects)

LAND USE	% subjects	No.of subjects
Residential	34.5	110
Shopping	10.0	32
Office	14.4	46
Main road	41.1	131

... contd

TYPE OF JUNCTION	% subjects	No.of subjects
Traffic light	51.1	163
Roundabout	32.0	102
Priority junction	16.9	54

Table 8.5 Predominant land use and type of junctions - Questions 3 & 4, Part 2 (319 Subjects)

8.7.1.2 Subjects' attitudes towards the area

Subjects' rating of the area as a place in which to live are shown in Table 8.6. The majority of subjects recorded positive opinions. 7.5% rated their attitude as 'very dissatisfied'. In Table 8.7 the items mentioned most frequently were noise, volume of traffic and exhaust fumes. It is clear that noise was the aspect of traffic which all subjects sharply disliked about the area. But in spite of the noise problem, the previous Table (8.6) shows how when the people personally benefited from the area, e.g. through shopping and children's schools, they evaluated the area positively.

8.7.1.3 Outside traffic noise - Question 6

Subjects were requested to evaluate the noise level of the road along which they lived and noticed most outside their property. The aim of this item was to identify the character and level of noise noticed throughout the selected area, and to verify the predominant source of noise. It is a guide towards people's reactions to noise nuisance.

The answers to this question, Table 8.8, show a common interest in all locations. 31.7% selected number 4 on the scale and 61.1% thought their road 'definitely unsatisfactory', (number 5 scale). This again indicates that there is a traffic noise problem in many areas.

	Area Rating				
	Very Satis -fied (1)	Fairly Satis -fied (2)	No Feeling Either way (3)	A Little Dissatis -fied (4)	Very Dissatis -fied (5)
% Subjects	21.3	29.5	27.6	14.1	7.5
No Subjects	68	94	88	45	24

	1	2	3
	yes	No	Don't Know
Level of noise	20	299	1
Closeness of shops, schools etc.	319	1	1
People in the area	279	32	8

Table 8.6 Rating of the area and satisfaction with noise level, public services and people - Questions 2 and 3 (319 Subjects)

		% subjects	No.of subjects
1	Noise	100	319
2	Volume of Traffic	9.5	292
3	Exhaust fumes	69.3	221
4	Traffic Accidents	10	33
5	Pedestrian Difficulty	6.9	22

Table 8.7 Subjects dissatisfied with noise and traffic - Question 4 (319 Subjects)

8.7.1.4 Indoors traffic noise - Question 7

Subjects were requested to indicate, on a five point scale, whether or not they noticed the noise inside their homes. This was an attempt to rate the level of noise inside the property. 34.2% selected the mid point on the scale (No.3), 28.5% selected number 4, while 11.3% selected number 5 (definitely unsatisfactory). See Table 8.9.

Thus, analysis of the characteristics of the study sample has established that there is a traffic noise problem for the Bath population.

	Outside Traffic Noise				
	Definitely Satisfactory (1)	Just Noticeable (2)	Moderate (3)	Noisy (4)	Definitely Unsatisfactory (5)
% Subjects	0	0.6	6.6	31.7	61.1
No.Subjects	0	2	21	101	195

Table 8.8 Outside traffic noise - Question 6 (319 Subjects)

	Indoor Traffic Noise				
	Definitely Satisfactory (1)	Just Noticeable (2)	Moderate (3)	Noisy (4)	Definitely Unsatisfactory (5)
% Subjects	2.51	23.5	34.2	28.5	11.3
No.Subjects	8	75	109	91	36

Table 8.9 Indoor traffic noise - Question 7 (319 Subjects)

8.7.2 Traffic Noise Sources

While the previous questions define traffic noise as a major environmental problem, the following will evaluate people's reaction to the main causes of traffic noise.

8.7.2.1 Environmental nuisance by classes of vehicles - Question 8

Subjects were asked to describe their evaluation of light, medium and heavy goods vehicles passing their property during the day and night. These responses are shown in Tables 8.10 - 8.12. The highest score ranged between number 3 and 4 for light vehicles, between 4 and 5 for medium vehicles and 5 (very annoyed) for heavy lorries. It is clear that the 37.6% who did not get annoyed by heavy lorries live under medium traffic conditions (light and medium vehicles only). All main road subjects treated the medium and heavy vehicles as very annoying.

The highest level of motor cycle annoyance ranged between numbers 3 and 4 (28.5% and 29.5%), Table 8.13.

The greatest proportion who blamed heavy lorries lived in London Road, Pulteney Road and Upper Bristol Road. The smallest proportion who blamed heavy lorries lived in Great Pulteney Street, Julian Road, The Paragon and Argyle Street.

It was confirmed that noise from heavy lorries causes the largest number of people to be annoyed, followed by medium and light vehicles respectively. Motorcycle noise caused noticeable annoyance in some areas.

	Car, Van and Light Goods Vehicle Noise				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	0	7.5	27.9	49.8	14.7
No.Subjects	0	24	89	159	47

Table 8.10 Assessment of light vehicle noise - Question 8.1

	Bus, Coach and Medium Goods Vehicle				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	0	1.3	9.4	32.2	57.1
No.Subjects	0	4	30	103	182

Table 8.11 Assessment of medium vehicle noise - Question 8.2
(319 Subjects)

	Heavy Lorry				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	37.6	0	0.3	10.3	51.7
No.Subjects	120	0	1	33	165

Table 8.12 Assessment of heavy vehicle noise - Question 8.3
(319 Subjects)

	Motor Cycle				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	9.4	13.5	28.5	29.5	19.1
No.Subjects	30	43	91	94	61

Table 8.13 Assessment of motor cycle noise - Question 8.4
(319 Subjects)

8.7.2.2 Vehicle maneuver nuisance - Question 9

The survey indicates that the highest ranking of noise nuisance resulted from vehicle maneuvers in urban areas (stop and go), Table 8.14 . The proportion of people who blamed junction noise was 84.7%. 36.4% of the subjects reported that they were 'extremely annoyed' by the noise from the nearest traffic light point, roundabout, or priority junction, (Number 5).

The 15.3% who indicated 'not annoyed' were either outside the junction range (more than 250 m) or in the shopping area where the people differed from the others in terms of sensitivity to junction noise. Table 8.15 shows, also, sources of annoyance from accelerating and decelerating vehicles, squealing tyres and interrupted traffic.

Answers to this question show a broad agreement between the subjects who live at some distance from signalised intersections, roundabouts, and priority junctions.

8.7.3 Traffic Noise Disturbance

The following will define the type of activities which noise interferes with.

8.7.3.1 Behavioural responses - Questions 11, 13, 14, 17, 18, 19

Table 8.16 shows 33.2% of the subjects stated that traffic was not causing windows or ornaments to vibrate or rattle.

Table 8.17 shows 68.7% of subjects reported that they kept their windows shut 'all the time'. 62.7% were between number 3 and 'all the time' on the scale, and mentioned that they were still disturbed when the windows were shut.

Answers to the general item about sleep disturbance show common agreement between the subjects. 78.4% mentioned their sleep disturbance (between 2 and 5 scale). 11.4% were disturbed 'all the time', and 24.5% indicated the middle of the scale. The people who indicated not at all on the scale (21.6%) mostly live in shopping areas where the daily life activity is normally between 08.00 and 19.00 hours, see Table 7.18.

Table 8.19 shows that 18.6% suffered interference with TV and radio, 19.8% interference with conversation and 17.2% interference with concentration, all the time.

	Noise from the Nearest Traffic Light, Roundabout and Priority Junction				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	15.3	12.3	14.7	21.3	36.4
No.Subjects	49	39	47	68	116

Table 8.14 Assessment of noise from junctions - Question 9.1 (319 Subjects)

	Noise From Accelerating/Decelerating Vehicles				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	21.9	13.8	24.5	23.5	16.3
No.Subjects	70	44	78	75	52

	Noise from Squealing Tyres				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	26.2	19.0	22.0	12.5	20.3
No.Subjects	83	61	70	40	65

... contd

	Noise from Interrupted Traffic				
	Not Annoyed (1)	Just Noticeable (2)	Moderate (3)	Annoyed (4)	Extremely Annoyed (5)
% Subjects	13.0	17.1	19.1	21.6	29.2
No.Subjects	41	55	61	69	93

Table 8.15 Assessment of noise from vehicle maneuvers - Questions 9.2-9.4 (319 Subjects)

	Vibration				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	33.2	30.7	19.2	7.8	9.1
No.Subjects	106	98	61	25	29

Table 8.16 Perception of vibration - Question 11 (319 Subjects)

	Shut the Window				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	0.6	1.3	7.5	21.9	68.7
No.Subjects	2	4	24	70	219

... contd

	Still disturbed when the window is shut				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	11.9	25.4	32.0	19.1	11.6
No.Subjects	38	81	102	61	37

Table 8.17 Window status - Questions 13 - 14 (319 Subjects)

	Disturbed Sleep				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	21.6	19.7	24.5	22.8	11.4
No.Subjects	69	63	78	73	36

	Move to the side of the house				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	24.5	16.6	18.8	17.5	22.6
No.Subjects	78	53	60	56	72

Table 8.18 Sleep disturbance - Questions 17 - 18 (319 Subjects)

	Interference with TV and Radio				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	19.0	26.0	22.3	14.1	18.6
No.Subjects	61	83	71	45	59

	Interference with Conversation				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	25.4	21.3	15.6	17.9	19.8
No.Subjects	81	68	50	57	63

	Interference with Concentration				
	Never (1)	Sometimes (2)	Often (3)	Very Often (4)	All the Time (5)
% Subjects	33.3	20.0	14.5	15.0	17.2
No.Subjects	106	64	46	48	55

Table 8.19 Interference with T.V. and Radio, conversation and concentration - Questions 19.1 - 19.3 (319 Subjects)

8.7.3.2 Effect of noise on the value of property - Question 22

It was attempted to get a clear picture of the effect of noise on property value. Table 8.20 shows that the highest percentage (70.2%), who were between the middle point on the scale and number 5 feel that noise influences the value of their property. Most of the affected subjects lived on the main roads (London Road), followed by some residential areas (Julian Road), and office areas (Manvers Street). 32% indicated 'very much reduced' on the scale.

	Financial value of Property				
	Not at all Reduced (1)	(2)	(3)	(4)	Very Much Reduced (5)
% Subjects	12.0	17.8	16.7	21.5	32.0
No.Subjects	38	57	53	69	102

Table 8.20 Financial value of property - Question 22 (319 Subjects)

8.7.3.3 Period of day - Questions 20 and 21

Subjects were requested to evaluate when they noticed, noise according to whether it was a weekday, weekend, and time of day.

The largest number of subjects suggested that traffic noise was most noticeable around their area during weekdays (78.7%). Noisiness was afternoon (95.9%) followed by moring (93.1%).

8.8 DOSE/RESPONSE RELATIONSHIP - STAGE TWO OF ANALYSIS

Previous sections comprised only the statistical characteristics of people's answers to different items of the questionnaire. The findings in these sections permitted general conclusions to be obtained. In order to get practical output for appraisal of noise annoyance, the following analysis has been carried out.

8.8.1 Establishment of Noise Annoyance Index

People's views on the quality of environmental noise exposure are an important issue especially at the planning stage. Thus, it is more helpful if these views are translated to an Annoyance Index. Measures of people's reaction as mentioned earlier are often based on people's ratings of the annoyance or dissatisfaction they experience because of noise. This method is essential, since systematic environmental evaluation demands that individual responses to each environmental noise factor be predicted. The total response of each individual is the aggregation of response to each factor, while the overall noise annoyance is the aggregation of total response of all the individuals affected.

For the purpose of this study, the numeric representation of two or more response items (e.g. Questions 6 & 7), which relate to particular effects, is defined as the Noise Annoyance Index.

At the moment, the relationship between people's annoyance and the physical environmental variables requires more investigation because no standard has been issued for measuring subjective responses to the environmental effects of traffic. In what follows the method of this study will be analysed.

From the questionnaire, four Noise Annoyance Indices could be evolved from the relevant questions:

(1) In questions 6 and 7 the subjects were directly asked about their annoyance caused by the general traffic noise levels which exist in their areas. The questions covered indoor and outdoor noise. The average of these two responses may provide a 5-point Noise Annoyance Index (NAI).

(2) In questions 8 and 9 the subjects were asked to rate the influence of the different components of traffic noise source. These included light, medium and heavy vehicles, motorcycles, junctions, acceleration, squealing tyres and interrupted flow. Again, the average value from these eight questions can provide a 5-point Source Annoyance Index (SAI).

(3) In questions 11,13,14,17,18,19 and 22 the subjects were asked to evaluate on a 5-point scale, the noise interference with various everyday activities in addition to the noise effects on the property value. The average response from these nine questions can also provide an Activity Disturbance Index (ADI).

(4) In order to deal with all aspects of the noise annoyance problem in built-up areas, and to consider the three elements of noise control (Source, Path and Receiver), an Overall Traffic Noise Annoyance index (OTNAI) was established. It is the average value of all the aforementioned indices (NAI, SAI & ADI - 19 Questions). Table 8.21 shows frequency of response along a 5-point scale for the 19 questions.

To assess noise exposure, L_{10}, L_{50}, L_{90} & L_{eq} were available . The task, therefore, was to find the best index as a predictor of people's reaction to road transport noise.

OTNAI, L_{10} & L_{eq} were found to be the most convenient indices. The details are presented in the following sections.

8.8.2 Relationships between questionnaire response and noise exposure indices

This section emphasises the relationships obtained from computation, utilising the aforementioned SPSS and MINITAB statistical systems. Reference is made to the correlation coefficients as introduced in Tables 8.22 - 8.23. The tables show clearly a significant level of correlation which exists in all cases.

For example all the values of the obtained correlation coefficients were higher than the critical value of R=0.113 at the 0.05 level of significance and R=0.148 at the 0.01 level of significance. Full details are as follows.

8.8.2.1 General noise levels (Questions 6 and 7)

Questions 6 and 7 were not considered to be just an indicator of the levels of traffic noise indoors & outdoors, but also a gauge of annoyance, as a subject who is not disturbed by noise will be much less aware of its presence. The highest correlation was found with L_{10} while L_{eq} gave slightly less, see Table 8.22. This result would seem to indicate that awareness of the traffic noise is most dependent on peaks when non-free flowing traffic is being considered. Figure 8.2 shows people's response to outdoor and indoor noise plotted against L_{10} dB(A).

8.8.2.2 Light, medium and heavy vehicles (Question 8)

The matter of whether noise annoyance increases with a specific class of motor vehicles was examined in question 8. Three types of traffic noise sources (L, M & H) were studied, and people's response to each kind of vehicles was correlated, see Tables 8.22 & 8.23. In all cases, it can be concluded that there is evidence that a difference in the composition of the traffic affects people's annoyance. People also differentiate between noise sources.

This conclusion reflects clearly the greater influence of traffic composition on urban environment when the traffic flow is interrupted. It also agrees with the findings of the physical measurements taken in this study, which gave more weight to the composition of traffic in urban areas and found differences between the noise levels emanating from the three vehicle categories. Figure 8.3 shows response to various noise sources plotted against L_{10} dB(A).

8.8.2.3 Road junctions (Question 9)

This question is taken as being an indicator of the dissatisfaction with the factors which are responsible for the generation of high noise levels in built-up situations.

The influence of various types of road junctions, e.g. roundabouts, was examined. Accelerating, squealing tyres and congestion of traffic were also considered. The high correlation was found with L_{10}, see Tables 8.22 - 8.23. L_{eq} showed slightly less significant interaction.

The output of this question was expected because the vehicles produce high noise levels when they accelerate away from junctions.

Again, the social survey results agree with the findings of the physical measurements which take into account the junctions, accelerations, etc.

Figure 8.4 shows response to different noise factors and distance from junctions. The range of influence of these factors is also obvious from the figure. For example, after 300m from junctions no one blamed the above factors.

8.8.2.4 Vibration (Question 11)

The correlation of Question 11 is illustrated in Tables 8.22 - 8.23. This indicates the link between incidence of vibration and the magnitude of noise levels. Vibration, therefore, can be considered an extension of noise and the presence of vibration can be taken as an indication of high noise levels. Also at high levels, the increase of reported existence of vibration can be explained by the difference in the number of medium and heavy vehicles in the traffic flow. These vehicles are the principal factors associated with the answers to the vibration question. For example, the people who answered 'highly annoyed' are exposed to heavy lorry traffic, especially in London Road.

8.8.2.5 Open or closed windows (Questions 13-14)

The objectives of these items were to evaluate the extent of the noise problem in connection with the building structure. Of course, the subjects who shut the window are dissatisfied with the outside noise pollution. Also the disturbance when the window is closed reflects the magnitude of the problem although poor insulation is also a factor.

Tables 8.22 -8.23 give the correlation coefficient of these question scores with noise indices and other items.

8.8.2.6 Sleep disturbance, building use and interference (Questions 17, 18, 19 & 22)

The answer to the sleep disturbance item (Question 17) was found to be dependent on traffic conditions and land use. L_{10} & L_{eq} gave the best correlation.

Question 18 also showed that people were using the rear part of buildings more,due to the noise level. Answers to this question were subject to building location and composition of traffic. See Tables 8.22 & 8.23 for various correlation coefficients which gave superiority to L_{10} & L_{eq}.

With reference to the interference questions, L_{10} & L_{eq} also correlated well, Tables 8.22. This reflects the magnitude of noise events, which determines the difficulty experienced in hearing TV & radio, in conversation and concentration.

The financial question illustrated how worried people are because of the damage which is caused to their property as a result of through traffic. Figure 8.5 shows people disturbance response versus L_{10}dB(A).

It is to be anticipated that response to the above questions would be greatest in areas of heavy traffic conditions, due to the clear effect of traffic. It is possible that a person with a high general dissatisfaction with noise could bias his response to these questions toward a greater dissatisfaction.

8.8.2.7 Effects of other factors on noise annoyance

As mentioned during the procedures of this research, the variables which constitute the built-up area structure are numerous and complex. There are also variations in their degree of influence on the level of noise people hear. Through the social survey, a lot of other data concerning the features of the study area were collected, including sex and age of the sample, land use classifications, type of junctions, location and type of buildings and storey where the subject lived (see Part 2 of the questionnaire). Different scales, lying between 1 and 5, were used for reporting the characteristics of these features. But it was obvious that these were not questions on people's attitude, as the 19 main questions in Part One were, for example the question of interference with people's conversation. However, it was thought that it would be useful to have some knowledge on the relationships of these non-attitude features and noise levels, since they are part of built-up area elements.

In areas of various land use, noise annoyance was found to be dependent on the conditions of traffic and other related variables. Noise annoyance increases in heavy traffic areas, i.e urban main roads, and is minimal in areas of light traffic, e.g. open spaces. The correlation between the noise level L_{10} and answers to the question on land use (Quest.3 part 2) was significant, R=0.31 (Above the critical value of R=0.113 at 0.05 level). Although it is not a people response question, the correlation coefficient indicates some kind of relation.

The item on types of junction (Quest.4 part 2) was also found to give R=0.36 (significant) with L_{10}. See also Table 8.5 for the details of land use and junctions.

In answer to the question about which floor the subject occupied, the noise annoyance was found to be steady with increase in the elevation of floor. This is probably because most of the buildings were low-rise (mostly 3 floors). The correlation coefficient between answers to the floor item (Quest.6 part 2) and L_{10} was R =-0.26 (significant). See Table 8.3 for details of floors.

The survey showed that there is a lack of any relation between sex or age and noise level perception L_{10} (see also Table 8.1).

The relationships of the above features with environmental noise were found to be minimal in contrast with the main items which were included in the 19 questions (see Tables 8.21 - 8.23) investigated earlier. Furthermore, it was difficult to establish an attitude scale like the ones used in the 19 questions, e.g. Good at No.1 and Bad at No.5. So, the scale of 1 to 2 in the question of sex, for example, does not mean any people response, but it is helpful for the purpose of analysis. In addition the strongest dependency of the above features on the other variables, for example, the passing of lorries through residential areas contribute to a loud level of annoyance which does not exist in similar areas win no through lorries.

For the purpose of this study, it was decided to concentrate on the basic attitude items, which were covered in 19 questions, in order to develop the noise annoyance prediction models (next section). However, most of the above non-attitude features were considered by the developed computer model in Chapter Nine as 'descriptive variables', because of the need to consider them at some design and planning stages.

	Question	Score %				
		Good				Bad
		1	2	3	4	5
1	Outside noise-Q.6	0.00	0.60	6.60	31.40	61.80
2	Indoor noise-Q.7	2.51	23.50	34.20	28.50	11.30
3	Car noise-Q.8.1	0.00	7.50	27.90	49.80	14.80
4	Bus & Coach noise-Q.8.2	0.00	1.30	9.50	32.10	57.10
5	Heavy lorry noise-Q.8.3	37.00	0.00	0.30	10.00	52.70
6	Motor cycle noise-Q.8.4	9.40	13.50	28.50	29.10	19.60
7	Junction noise-Q.9.1	15.30	12.10	14.70	21.40	56.50
8	Accelerating noise-Q.9.2	21.90	13.80	24.50	23.50	16.30
9	Squealing tyre noise-Q.9.3	26.20	19.00	22.00	12.50	20.30
10	Interrupted traffic noise-Q.9.4	13.00	17.00	19.10	21.60	29.20
11	Vibration-Q.11	30.20	30.00	20.90	7.80	11.10
12	Shut window-Q.13	0.60	1.30	7.50	21.90	68.70
13	Closed window disturbance-Q.14	11.90	25.40	32.00	19.10	11.60
14	Sleep disturbance-Q.17	21.60	19.70	24.50	22.80	11.40
15	Building use-Q.18	24.50	16.60	18.80	17.50	22.60
16	Interference with T.V.-Q.19.1	19.00	26.00	22.30	14.10	18.60
17	Interference with conversation-Q.19.2	25.30	21.30	15.60	18.00	19.80
18	Interference with concentration-Q.19.3	33.30	20.00	14.50	15.00	17.20
19	Financial effects-Q.22	13.00	17.80	16.70	21.50	32.00
	Total	307.71	286.40	360.00	418.40	529.30
	Mean %	16.195	15.0737	18.947	22.021	27.858

Table 8.21 Frequency of response along 5-point scale for 19 questions (OTNAI components) - 319 Subjects

Annoyance Score	Noise index dB(A)			
	L_{10}	L_{50}	L_{90}	L_{eq}
Q.6 Outside noise	0.650	0.478	0.451	0.587
Q.7 Indoor noise	0.500	0.472	0.454	0.488
Q.8.1 Car noise	0.382	0.296	0.254	0.377
Q.8.2 Bus and Coach noise	0.350	0.281	0.246	0.312
Q.8.3 Heavy lorry noise	0.410	0.318	0.264	0.410
Q.8.4 Motor cycle noise	0.320	0.275	0.264	0.262
Q.9.1 Junction noise	-0.750	-0.571	-0.520	-0.600
Q.9.2 Accelerating noise	-0.680	-0.600	-0.562	-0.624
Q.9.3 Squealing tyre noise	-0.663	-0.654	-0.624	-0.668
Q.9.4 Interrupted traffic noise	-0.554	-0.520	-0.484	-0.513
Q.11 Vibration	0.570	0.569	0.542	0.569
Q.13 Shut window	0.450	0.420	0.394	0.440
Q.14 Closed window disturbance	0.559	0.570	0.550	0.560
Q.17 Sleep disturbance	0.600	0.560	0.540	0.596
Q.18 Building use	0.533	0.510	0.475	0.496
Q.19.1 Interference with T.V.	0.550	0.530	0.500	0.538
Q.19.2 Interference with conversation	0.560	0.551	0.531	0.560
Q.19.3 Interference with concentration	0.540	0.530	0.520	0.533
Q.22 Financial effects	0.496	0.490	0.489	0.492

Table 8.22 Correlation coefficients of the 19 annoyance scores & noise indices (OTNAI components)
R=0.113 at the 0.05 level of significance
R=0.148 at the 0.01 level of significance
No. of Subjects = 319

	Q 7	Q 8.1	Q 8.2	Q 8.3	Q 8.4	Q 9.1	Q 9.2	Q 9.3	Q 9.4	Q 11	Q 13	Q 14	Q 17	Q 18	Q 19.1	Q 19.2	Q 19.3	Q 22
Q.6	0.584	0.314	0.210	0.329	0.227	0.142	0.255	0.360	0.359	0.471	0.450	0.504	0.500	0.513	0.500	0.440	0.410	0.550
Q.7		0.354	0.201	0.279	0.313	0.200	0.286	0.409	0.438	0.655	0.371	0.650	0.610	0.594	0.572	0.580	0.580	0.610
Q.8.1			0.707	0.576	0.483	0.377	0.472	0.382	0.365	0.371	0.587	0.430	0.412	0.373	0.450	0.380	0.331	0.300
Q.8.2				0.673	0.529	0.377	0.458	0.333	0.295	0.269	0.543	0.300	0.250	0.280	0.333	0.280	0.240	0.190
Q.8.3					0.353	0.272	0.304	0.227	0.136	0.356	0.511	0.254	0.400	0.360	0.410	0.217	0.172	0.192
Q.8.4						0.151	0.314	0.339	0.384	0.462	0.455	0.467	0.401	0.410	0.780	0.500	0.490	0.410
Q.9.1							0.770	0.600	0.512	0.120	0.361	0.230	0.210	0.230	0.211	0.200	0.160	0.210
Q.9.2								0.740	0.650	0.330	0.484	0.410	0.350	0.380	0.400	0.400	0.390	0.371
Q.9.3									0.763	0.532	0.410	0.532	0.540	0.550	0.550	0.580	0.550	0.540
Q.9.4										0.440	0.380	0.513	0.400	0.460	0.450	0.600	0.600	0.540
Q.11											0.433	0.760	0.820	0.730	0.770	0.750	0.750	0.650
Q.13												0.590	0.460	0.345	0.444	0.360	0.340	0.443
Q.14													0.770	0.722	0.730	0.720	0.700	0.723
Q.17														0.792	0.810	0.710	0.690	0.692
Q.18															0.860	0.750	0.700	0.791
Q.19.1																0.840	0.783	0.692
Q.19.2																	0.933	0.678
Q.19.3																		0.674

Table 8.23 Correlation coefficients between 19 item scores of the Questionnaire (OTNAI components)

R=0.113 at the 0.05 level of significance

R=0.148 at the 0.01 level of significance

8.8.3 Prediction of overall traffic noise annoyance

8.8.3.1 Prediction models

This section deals with the assessment of the most suitable noise annoyance and noise exposure indices. The evaluation was made according to the obtained correlation coefficients which were reported previously.

The Overall Traffic Noise Annoyance Index, OTNAI, proved to have the highest level of correlation with noise exposure indices and independent variables. In additions, the high level of correlation which obtained between the components of OTNAI (Table 8.23) gives additional credit to the reliability of this index, as based on questions related to annoyance to high degree. Table 8.24 shows correlation coefficients between various noise exposure and noise annoyance indices. With regard to noise exposure, L_{10} proved to correlate significantly with people's reaction. L_{eq} also showed good correlation although its level of interaction is slightly less than L_{10} in some cases. In spite of this, it is statistically significant.

Annoyance index	Noise Index dB(A)			
	L_{10}	L_{50}	L_{90}	L_{eq}
NAI	0.547	0.521	0.497	0.530
SAI	0.781	0.730	0.686	0.774
ADI	0.630	0.600	0.580	0.610
OTNAI	0.840	0.734	0.6858	0.785

Table 8.24 Correlation coefficients between various noise exposure and noise annoyance indices. R=0.113 at the 0.05 level of significance and R=0.148 at the 0.01 level of significance.

Therefore, OTNAI, L_{10} & L_{eq} have been considered as the main indices of this study for traffic noise annoyance and noise exposure. This conclusion also places more confidence in the prediction methods developed in this study, which have been described in previous chapters.

Figures 8.6 - 8.9 illustrate frequency of response to the components of OTNAI.

The correlation between OTNAI and noise levels which is presented in Table 8.24, is shown in Figure 8.10. This graph was found to be the best dose/response relationship. The mathematical expression to describe the relationship is:

$$OTNAI = 0.175\,(L_{10}) - 10.5 \qquad \ldots (8.1)$$

where:

R = 0.840 (significant)

st.dev. = 0.565

Other noise exposure indices were also evaluated as follows:

$$OTNAI = 0.173\,(L_{eq}) - 9.89 \qquad \ldots (8.2)$$

where:

R = 0.785 (significant)

st.dev. = 0.574

$$OTNAI = 0.149\,(L_{50}) - 7.51 \qquad \ldots (8.3)$$

where:

R = 0.734 (significant)

st.dev. = 0.590

It is clear that the above models gave a significant correlation coefficients especially L_{10} and L_{eq} models, in contrast with the critical value of R which equals 0.0113 at the 0.05 level of significance and equals 0.148 at the 0.01 and of significance. In addition, a test of a null hypothesis was also employed to check the significance of the models, by comparing the Variance Ratio with the f-distribution on appropriate degree of freedom. For OTNAI in terms of L_{10} the Variance Ratio=119.5512/0.3192=374.5. The f-distribution=$f(1,317)_{0.1\%}$ = < 11.4 < 374.5 (significant). A 99% confidence interval estimate (Section 7.3.2.1) was also employed to check the significance of the model. The true slope is estimated with 99% confidence to be between +0.199 and +0.151. Thus, there is a significant positive relationship between OTNAI and the values predicted by the model in terms of L_{10}. L_{eq} model also gave VR= 368.5 and true slope between +0.197 and 0.148. The VR for L_{50} model is 323.7 while the true slope between +0.17 and +0.13. The conclusion can be drawn that there is a significant correlation (99% confidence) between the measured values and values calculated by OTNAI in terms of noise exposure indices.

The residual values for the above models ranged between ±1.4 for 95% of cases. The values at low end of noise level (less than 72 dB(A)) indicate supersensitivity in people' answers. This was at 17 sites. By removal the 17 site measurements, no significant change was obtained. Thus, it was believed that the above models, especially L_{10} and L_{eq} models, were the best prediction tools. Figure 8.11 shows OTNAI plotted against L_{eq}.

The 12 hour values of L_{10}, L_{eq} and L_{50} were tested against OTNAI. The results showed that there is no significant change in the values of correlation coefficients, in spite of small variation in the empirical constants. This is probably because 12-hour surveys usually represent the convenient method for any traffic study from the traffic engineering point of view (Section 5.8). Besides, it includes the daily highest noise level periods.

In addition, OTNAI gave a high level of correlation even with independent variables. For example, the correlation coefficient between OTNAI and traffic flow was 0.760, while the correlation with traffic composition (L+6M+10H) was

R=0.876, see Figure 8.12. The distance from junction variable also gave R=0.776 with OTNAI. The correlation coefficient between speed of traffic and OTNAI was R=0.563.

So, these findings indicate the possibility of using the above models especially 8.1 and 8.2, for a wide range planning and design purposes.

8.8.3.2 Comparison with previous surveys

Since no previous studies have systematically considered 19 response items to establish OTNAI, direct comparison of results is not possible. However, a general investigation is of benefit.

The main indices developed for assessing traffic noise, as described in Chapter 4, are L_{10}, L_{eq}, TNI and L_{np}. Researchers all over the world have given more weight to L_{10} and L_{eq} as the best predictors (Langdon and Buller., 1977; Croome 1977; Schultz 1982). This is also confirmed even by a laboratory study of traffic noise annoyance (Rice, Sullivan, Charles and Gordon, 1974).

The correlation coefficient between individual response data and noise indices was found to be quite low by previous studies. Moreover, there are differences across the surveys in the level of predictive ability of the indices. For example, the correlation with individual data in the Griffiths and Langdon (1968) study was R = 0.3, while Lambert Simonnet and Vallet, (1984) were reported R=0.6. Some researchers have given reasons for the lack of correlation between the individual subjective responses and noise exposure. For example, in a survey of noise annoyance in central London (McKennell and Hunt, 1966). The main reasons given there were firstly, 'attenuation of measurement', i.e attenuation at the respondents' homes due to their difference in distance from the measuring point. Secondly, 'Statistical distribution over the noise levels', i.e the distribution of the respondents over the noise level classes was not uniform.

In connection with this study L_{10} & L_{eq} were found as the best indices during the physical and social surveys (The study has not reported the results of TNI & L_{np} as there were no significant correlations obtained). The correlation of L_{10} and L_{eq} with people response were satisfactory as listed in Table 8.22.

With regard to dose/response relationships, numerous investigations have been carried out in a number of countries. The findings of these studies may be considered to fall into two areas. In these, some researchers measure people's response in terms of mean ratings such as Langdon and Buller (1977) in Britain, while the others measure it in terms of percentage of subjects reporting a high level of annoyance such as Schultz (1982) in America. In general, L_{10} and L_{eq} were taken as representing the total traffic noise level. Relationship in terms of percentage of heavy vehicles (Log_{10} %HV) without reference to the noise level has also been found to correlate with people reaction by Langdon and Buller (1977). However, the Langdon study is one of few for restricted traffic and it concentrates on the importance of heavy vehicles only.

In this study, the people who own their houses, e.g. in London Road, concentrated mainly on the effects of heavy lorries, vibration and presence of traffic lights. They chose the high point of the scale. On the other hand some people who live in council houses or cheap rented accommodation selected numbers three or four of the scale. They were pleased with their houses in spite of the high level of noise and the damage which is caused to the buildings as a result of the vibration. Thus, selecting only the 'highly annoyed' in the survey (as reported by Schultz) is not truly representative of the overall situation in built-up areas. Further, there are many unanswered questions, concerning the definition of 'highly annoyed', e.g. are those who answered number five of the scale only, numbers four and five or numbers three to five.

All of these numbers indicate different percentages of response and depend on various circumstances .

Concerning the percentage of heavy vehicles only (as reported by Langdon), in this study SAI which represented the response to various kinds of vehicles and to factors influencing the generation of a high level of noise occupied the second level of satisfactory correlation, after OTNAI. This is certainly because of the positions of SAI components in urban environment. But, the consideration of SAI alone for noise annoyance evaluation was found to be insufficiently representative in spite of its contribution to the loud level of noise. It was found that response to total noise exposure, outdoors or indoors, depends also on other factors which are responsible for the final level of noise heard by the subjects. For example, people who are regularly disturbed by the accelerating of traffic, rate themselves as 'extremely annoyed' even though their total noise exposure is comparatively low.

Thus, as far as this study is concerned OTNAI was found to be the best representative of the whole problem of traffic noise. Equations 8.1 -8.3 were, therefore, the best models for traffic noise annoyance in restricted flow situations.

OTNAI had a higher level of correlation probably because it is based on all aspects of the noise problem in built-up areas. It was established in terms of 19 response questions which covered the three elements of noise (source, path and receiver). These are the SAI which represents the source components (8 questions) and NAI represents propagated noise (2 questions), which depends on urban area features and source ingredients. ADI was also taken into account as an indicator of receiver responses (9 questions). There is probably another reason for the good performance of OTNAI, which is that the measurements of noise levels were made along the accelerating and decelerating streams of traffic and the interviews were carried out with subject locations at short distances from the measurement sites. Thus, the noise level at the subject's address was roughly the same as that at the physical measurement site. Long distances between interview positions and measurement sites were found to increase the degree of error by many researchers. So the continuous building facades on both sides of the road networks, and the uniform distance from the nearside kerb (maximum 8m) are other reasons for the high correlation of OTNAI. The period of sampling (30-minute) is probably another reason why this method represents the real situation, because the subjects were exposed to noise levels the same as those measured.

8.8.3.3 Estimated Noise Annoyance and Changes in Traffic Composition

This section deals with the relationship between changes in the composition of traffic and the estimated noise annoyance and exposure.

Two typical roads were selected for this objective. Traffic noise exposure and annoyance reactions were evaluated. The investigation was associated with different percentages of heavy and medium vehicles, since these vehicles contribute to the high level of noise in built-up areas. In addition, most of current researches have been directed toward the improvement of noise emission of heavy vehicles (Chapter 2).

Table 8.25 shows how variations in the percentage of medium and heavy vehicles affect the level of traffic noise and the estimated OTNAI. It is clear that tremendous changes are required in the structure of traffic to achieve significant improvements in the overall level of noise and thereby to minimise public reaction. For example, reduction of P from 10% to 5% on an urban main road would result in only a 0.91 dB(A) reduction in noise exposure level, and 0.16 in traffic noise annoyance. Even in the cases where P=0, the level of noise still exceeds the recommended limits (e.g. the official British recommended level is L_{10} = 68 dB(A) - see Section 4.5).

The above investigation indicates that people's annoyance will continue even if there are no vehicles which are individually noisy, e.g. heavy vehicles. This means that the traffic noise problem cannot be abated solely by minimising the noise emission of heavy lorries, which are the target of current programmes in many countries (Chapter 2).

Thus, an effective noise policy in any urban and suburban areas would require abatement of the total road traffic noise level as it operates in real situations. This policy is necessary to satisfy people's demand for adequate protection against traffic noise disturbance. This limited practical conclusion, again increases the importance of design and planning for road transport operations as discussed in Chapter 3.

Road	Q v/h	P %	Predicted L_{10}dB(A)	Predicted OTNAI
Urban main road V=33 km/h J=78.6m N=2.3m F=15.8	2750	0	79.89	3.481
		5	80.81	3.642
		10	81.72	3.800
		20	83.55	4.120
Office area road V=18.99 km/h J=37m N=3.3m F=10.80	1200	0	78.25	3.190
		5	79.20	3.360
		10	80.1	3.520
		20	81.91	3.830

Table 8.25 Effect of changes in the percentage of medium and heavy vehicles on the predicted noise level and noise annoyance (Based on urban & suburban model, Eq 7.2 & OTNAI model, Eq 8.1)

8.9 Summary

Attempts to control traffic noise in built-up environments have been hampered by insufficient knowledge of various complex interactions between traffic noise level and various negative people responses to this noise. People's reaction to traffic noise annoyance were studied in the urban area of Bath. The finding indicated that substantially high noise levels exists in a great part of the city and more specifically in the urban main road areas. 18-hour noise measurements were carried out at 48 sites selected as representative of various land use and conditions.

The social survey was performed by means of an appropriate questionnaire (73 items), on a selected sample of 319 individuals, by means of personal interviews.

The first stage of analysis involved the characteristics of the study sample. The result indicated that traffic noise seems to be a major environmental problem. Traffic noise in general; and medium and heavy vehicles, motor cycles, junctions, acceleration and other vehicle maneuvers in particular were the main noise source reported. Vibration, windows open or closed, sleep disturbance and interference with TV, concentration and conversation were the human activities reported as being disturbed by traffic noise.

In a second stage of analysis the noise exposure indices were correlated to each questionnaire item. Other variables were also correlated in the same manner. L_{10} & L_{eq} were defined as the best predictors.

Relationships between annoyance and physical measurements of noise level were found. Four noise annoyance indices were developed from the relevant questions of the questionnaire. The Overall Traffic Noise Annoyance Index (OTNAI) proved to have the highest correlation with noise indices and the considered independent variables.

OTNAI was the average value of 19 questions representing all aspects of noise annoyance in built-up areas, such as source and its causes, level of propagated noise and people's activities.

Three models for the prediction of overall traffic noise annoyance were established. They related OTNAI to L_{10}, L_{eq} & L_{50}. Apart from L_{50}, they gave a high level of correlation. Comparison with previous surveys was also made.

Application of the developed noise annoyance (Eq.8.1) and noise exposure (Eq.7.2) models has shown that a traffic noise abatement policy would be the most convenient protection against traffic noise disturbance. This should include the consideration of traffic noise in the process of transportation planning, road building, urban planning and building construction. Meanwhile noise problems cannot be minimised solely by the control of noisy vehicles.

Finally as far as this study is concerned, OTNAI models have proved their superiority as a comprehensive prediction tool based on a wide range of built-up area conditions. They are also practical and accurate for the purpose of design and planning.

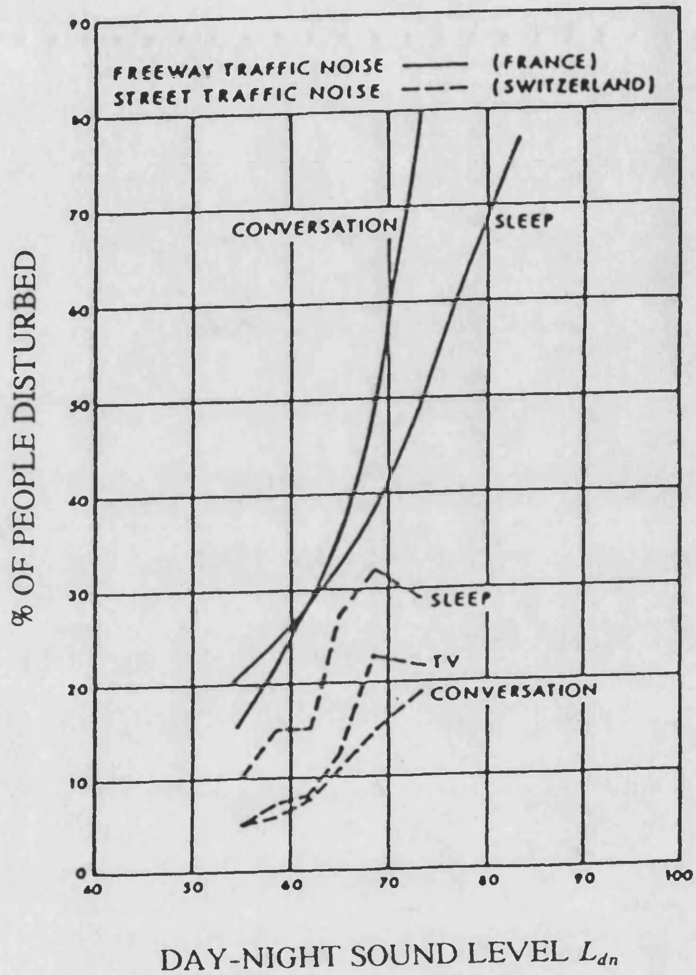


Figure 8.1 Interferene by street and freeway traffic noise with conversation, TV and sleep (Schultz, 1982)

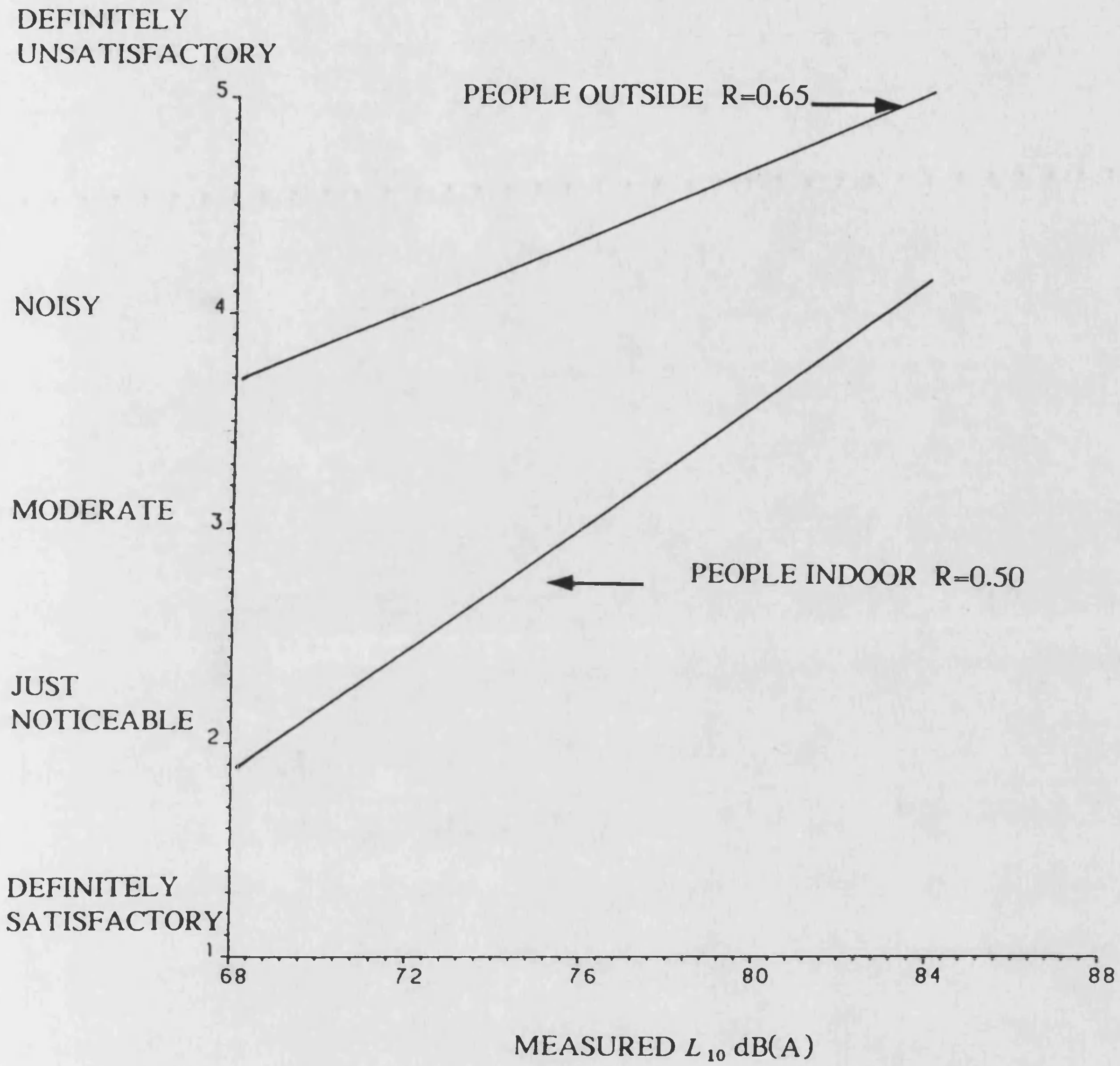


Figure 8.2 Relationship between people's response to indoor and outdoor noise and measured noise level L_{10} dB(A)

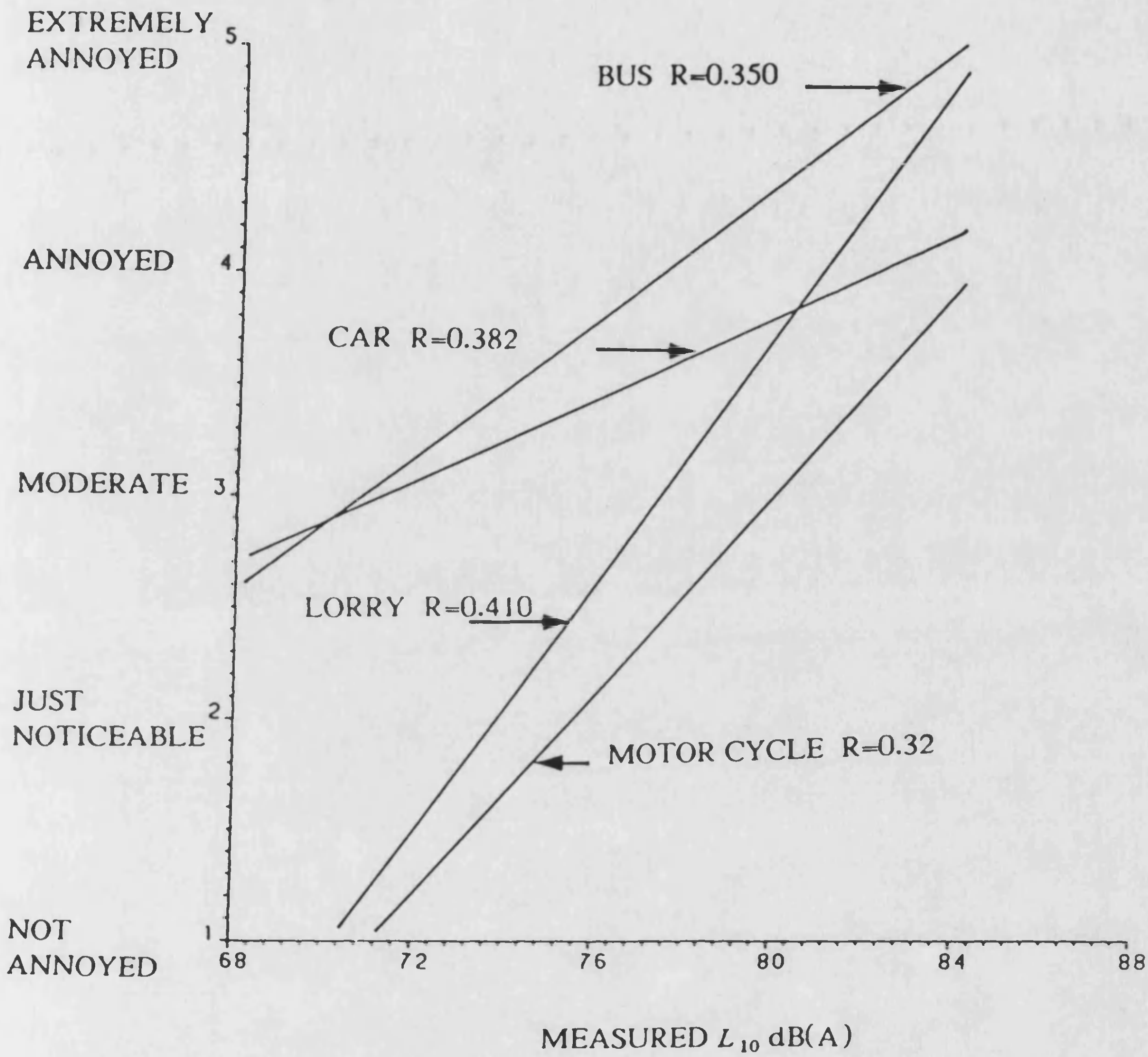


Figure 8.3 Relationship between people's response to various noise sources and measured noise level L_{10} dB(A)

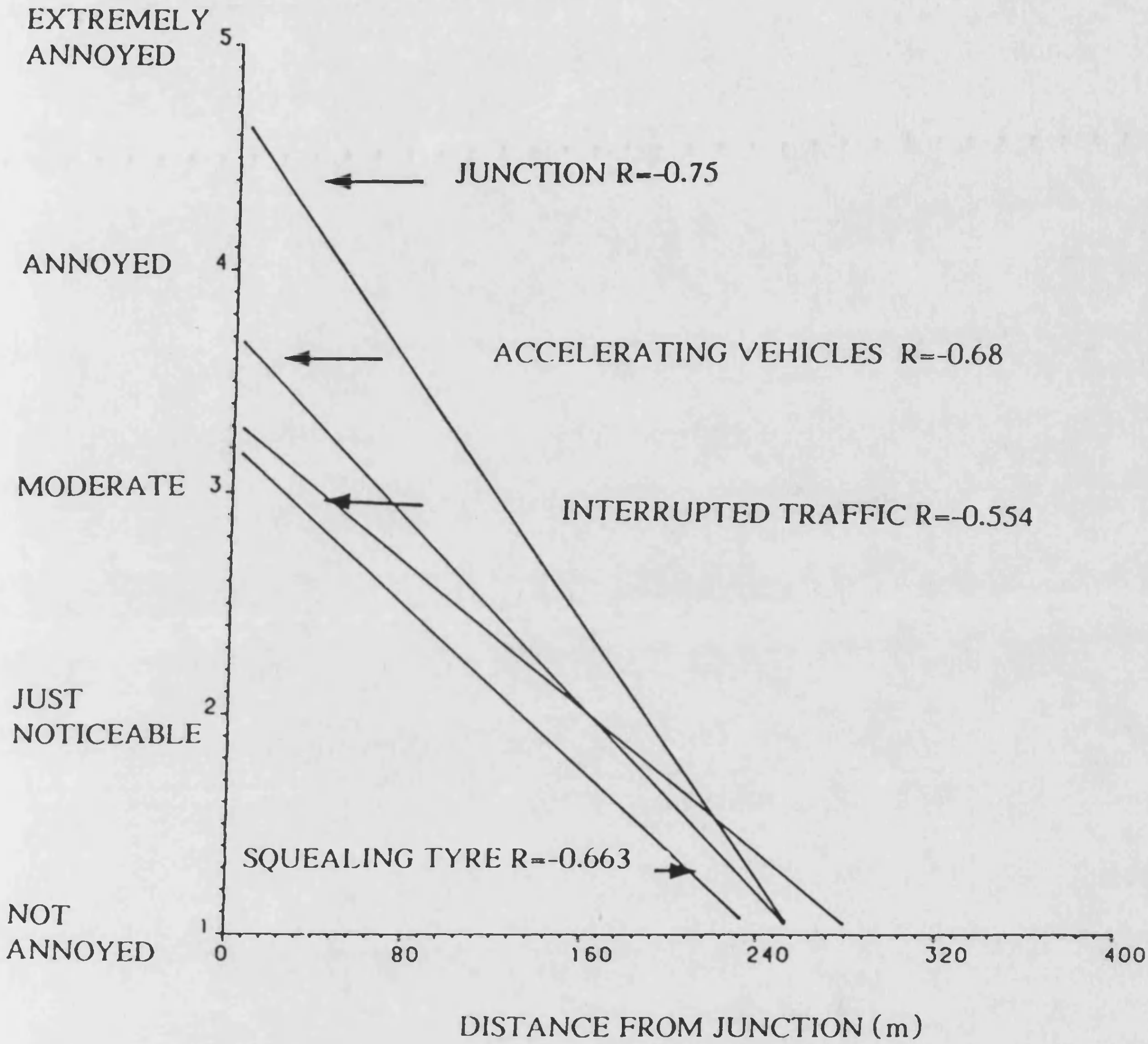


Figure 8.4 Response to different noise factors and distance from junctions

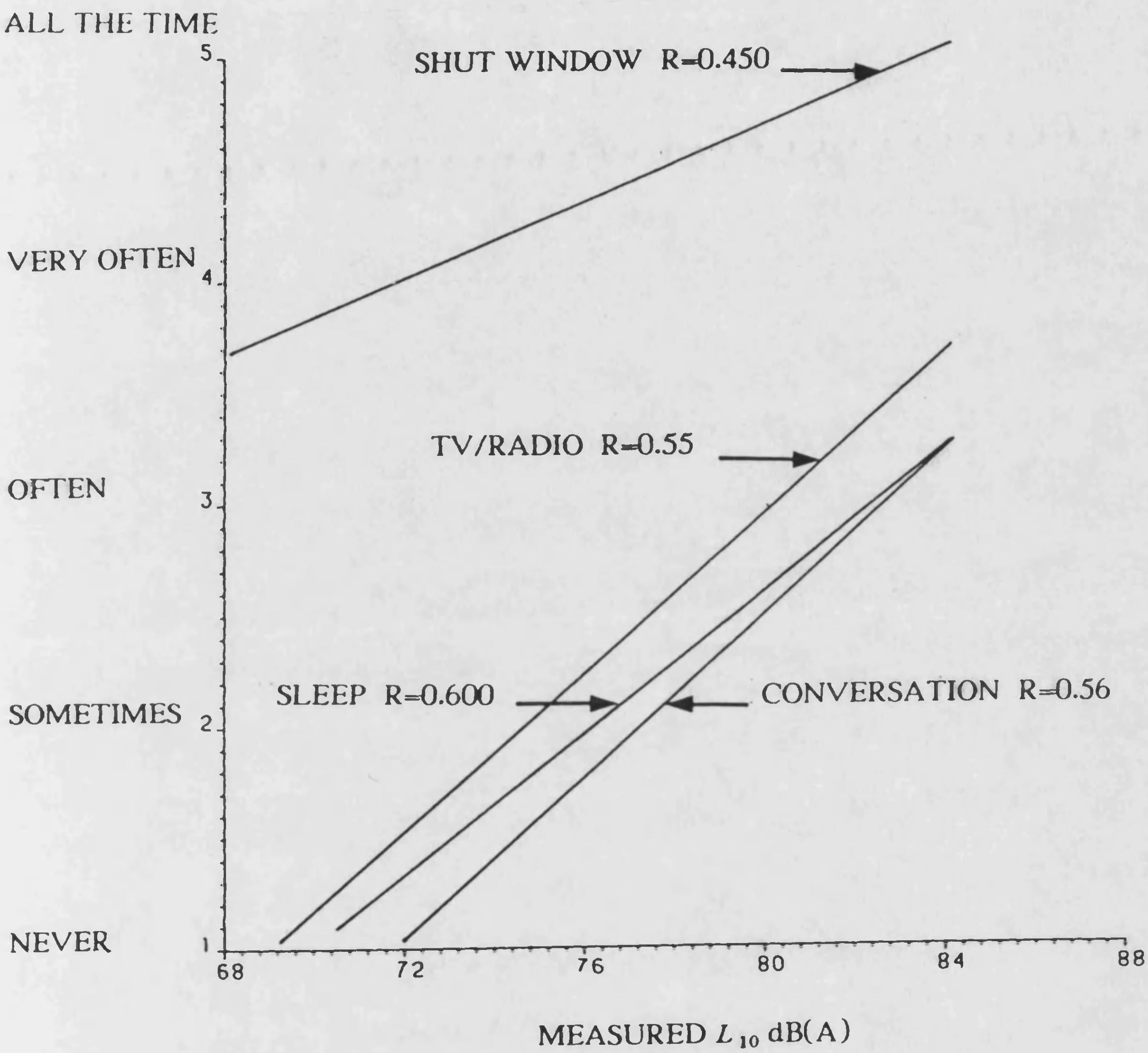


Figure 8.5 People's disturbance response versus measured noise level, L_{10} dB(A)

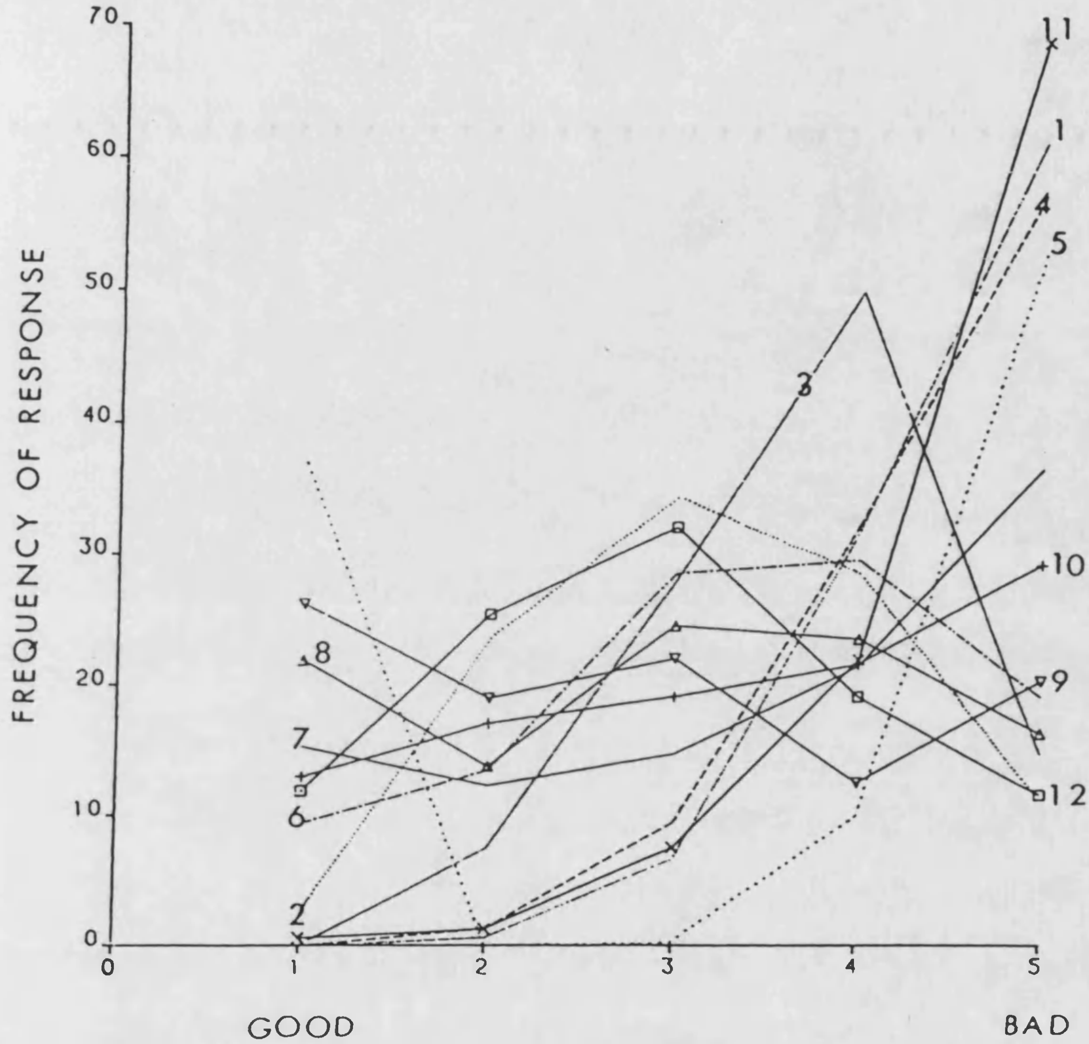


Figure 8.6 Frequency of response to the components of OTNAI (12 Questions)

1.People outside	2.People indoor
3.Car	4.Bus
5.Lorry	6.Motor cycle
7.Junction noise	8.Accelerating noise
9.Squealing tyre	10.Interrupted traffic
11.Shut window	12.Closed window disturbance

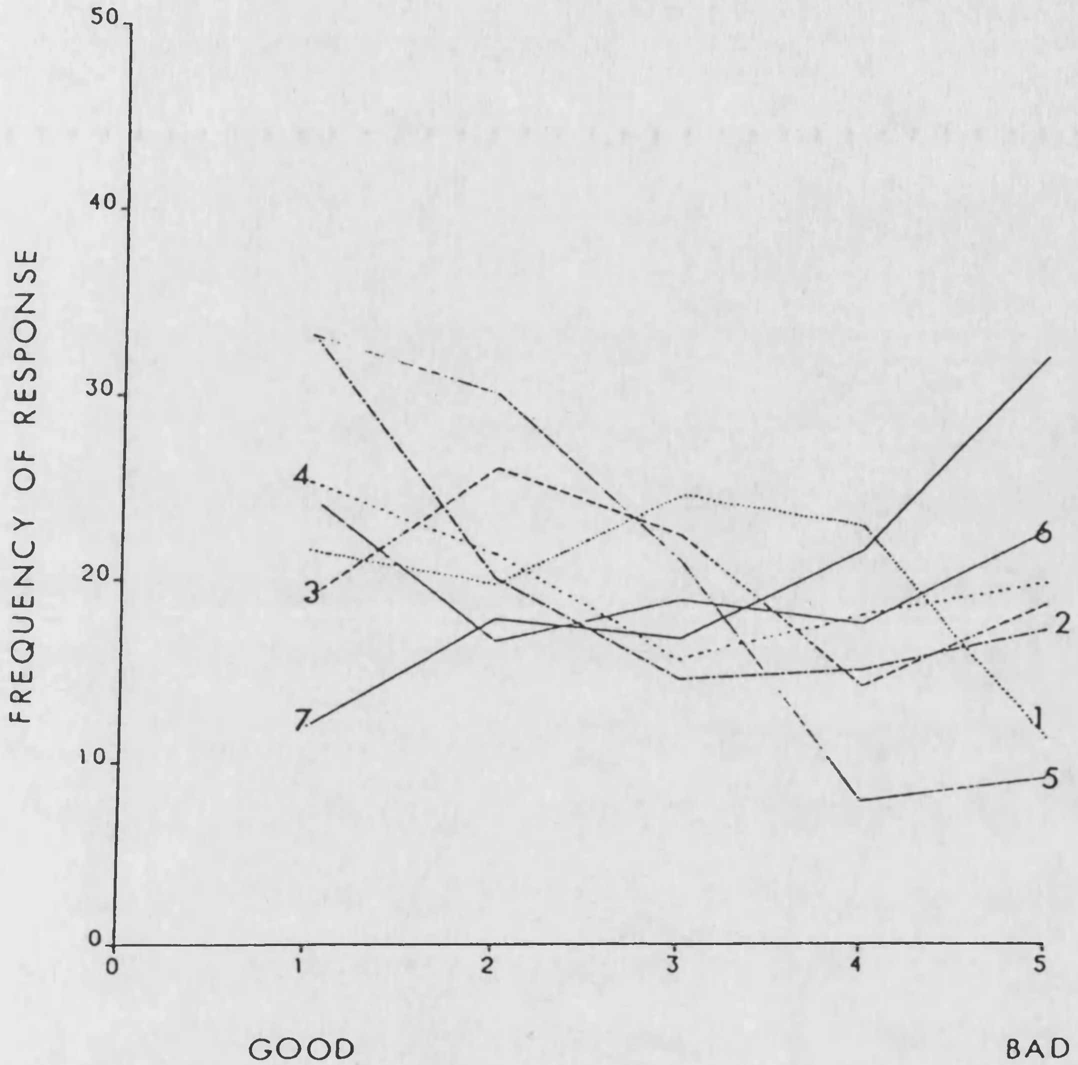


Figure 8.7 Frequency of response to the components of OTNAI (7 Questions)

1.Sleep
2.Concentration
3.TV and radio
4.Conversation
5.Vibration
6.Building use
7.Financial effects

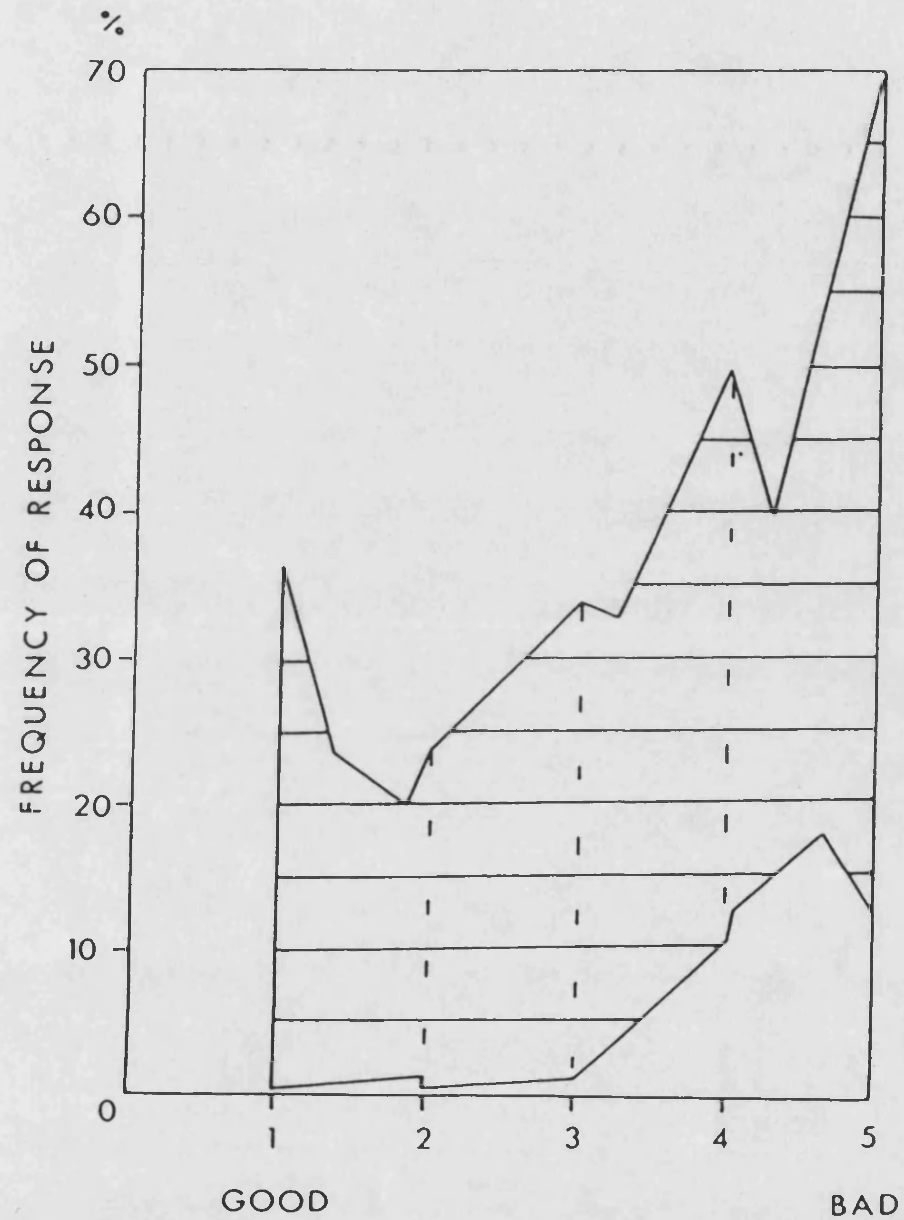


Figure 8.8 Envelope showing range of response to the 12 components of OTNAI - Figure 8.6

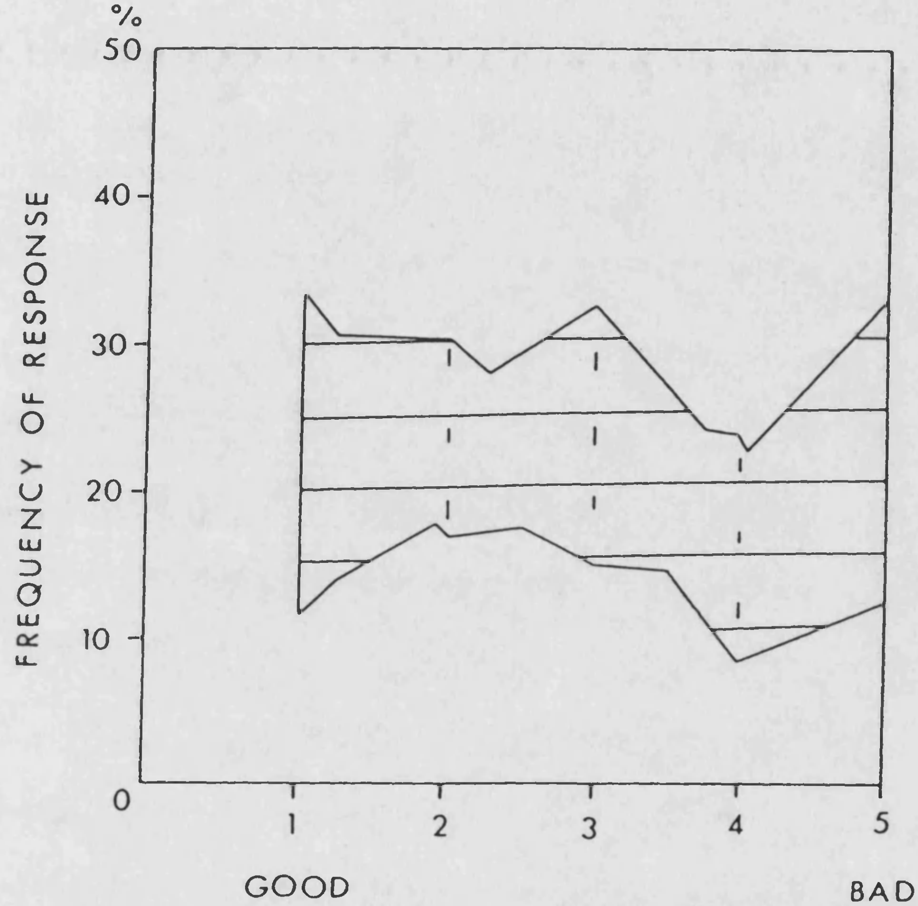


Figure 8.9 Envelope showing range of disturbance to the 7 components of OTNAI - Figure 8.7

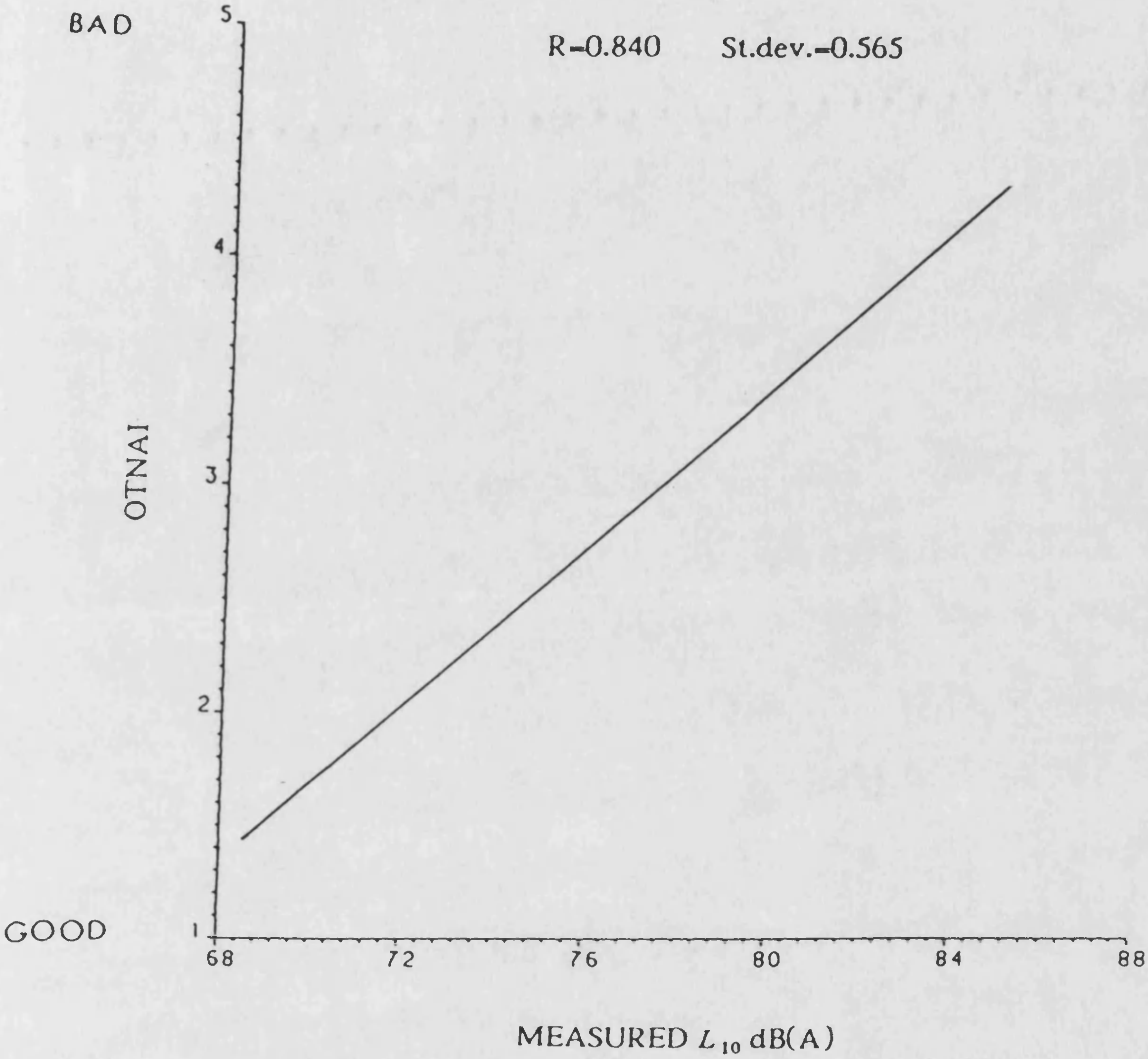


Figure 8.10 OTNAI versus measured noise level, L_{10} dB(A)

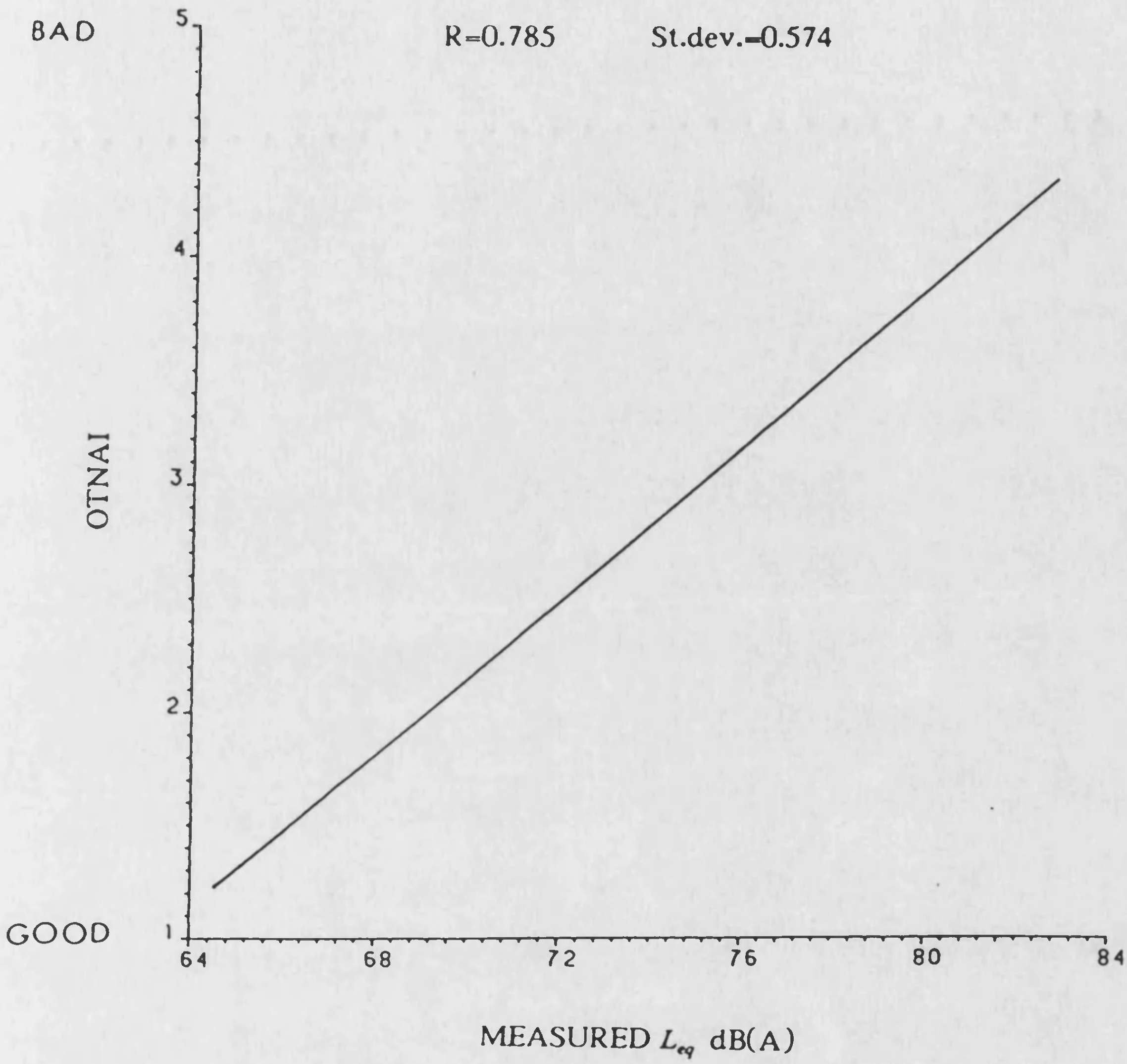


Figure 8.11 OTNAI versus measured noise level, L_{eq} dB(A)

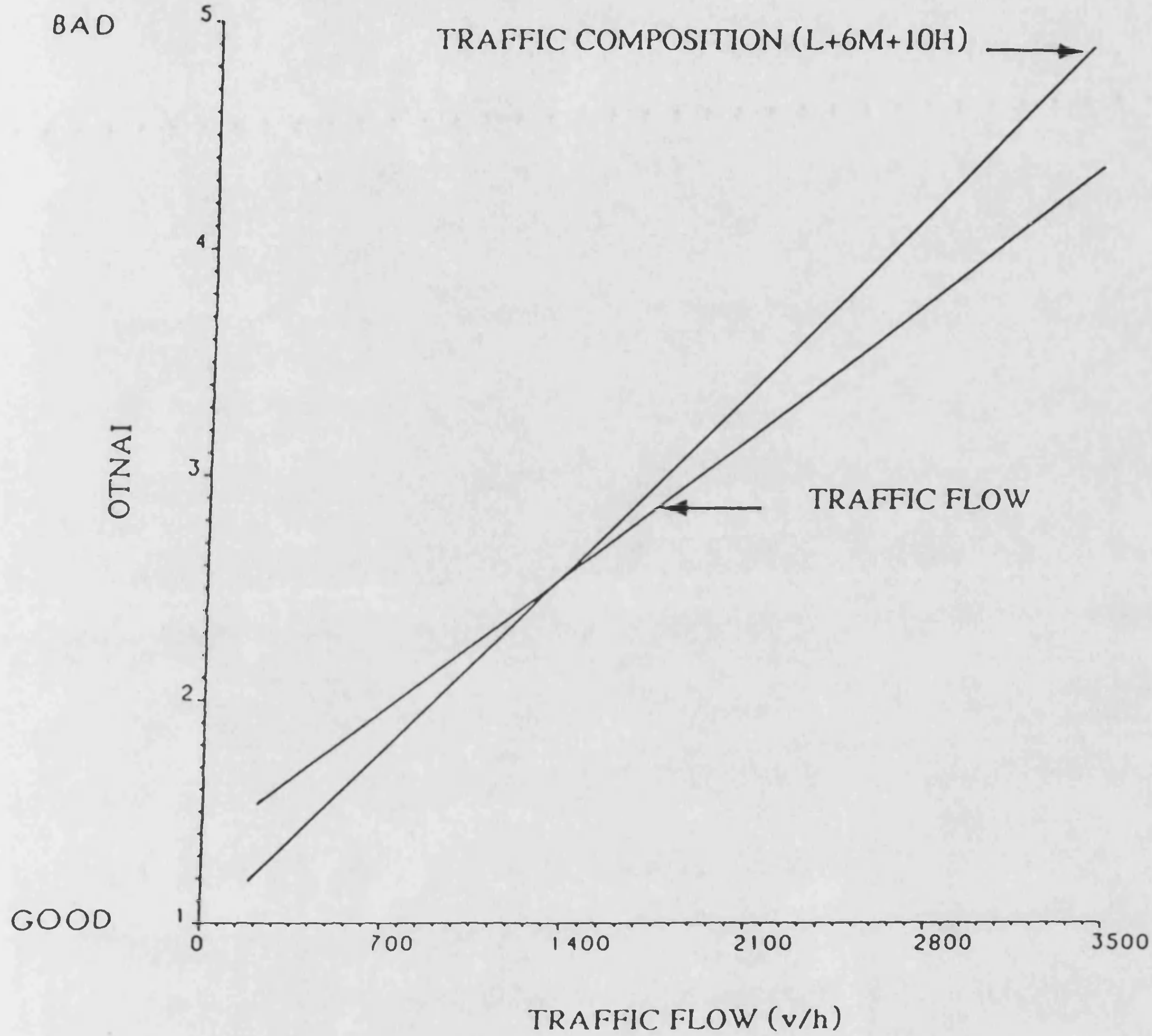


Figure 8.12 Relationships of OTNAI and traffic flow and composition

CHAPTER NINE

A COMPUTER MODEL TO ASSESS AND PREDICT ROAD TRANSPORT NOISE IN BUILD-UP AREAS

9.1 INTRODUCTION

This chapter deals with the establishment of a comprehensive computer model (UBSUB) to assess and predict traffic noise exposure and noise annoyance, associated with all the common variables of urban and suburban environments. It also reports the development of a graphic computer model (GRUS) capable of evaluating the effects on the level of noise due to changes in the performance of the individual variables, in order to maintain the recommended noise climate by operating the best system for the comfort and safety of the public.

The accelerating progress in computer science and its availability in recent years make the computer model, if it is based on real field studies, a very efficient method of analysing a large quantity of data or a variety of conditions. The computer model can assess phenomena which are too complex to be introduced by mathematical equations alone. It can be used as an aid to save both time and money. To be used with confidence, the computer model requires detailed input information and reliable empirically derived methods. Once these exist, a program that will faithfully evaluate the behaviour of the system can be designed. The model also must meet certain criteria. It must be: easy to use; simple and not using too much computer time; accurate and representative of the real situation. For traffic noise in restricted flow situations a review of the available literature (Chapter 4) indicates that apart from a computer simulation model for signalised intersections there is no common model.

With regard to this study, preceding chapters have reported the development of new prediction models. These models showed accuracy and reliability and were based on significant planning and design components. But, in spite of these advantages, there are still unanswered questions concerning other factors required for the execution of a thorough scheme. The 'descriptive variables' which are listed in Section 5.9 and 9.3.1 are an example of these factors. Such variables cannot easily be quantified, e.g. Land use. Thus, they cannot be covered by mathematical methods as the other variables are, despite their being necessary at some planning stages which need detailed information, e.g. transportation planning, traffic management and urban planning (see Section 3.4). So the large number of related independent variables in built-up areas, and the difficulty of covering all of them in one mathematical formula, necessitated the development of a comprehensive computer model such as UBSUB to enable the generated noise from vehicular traffic in a complex built-up environment to be studied. In addition, for practical application it is convenient to have an instrument which estimates the noise levels at the same time, in terms of the commonly used environmental noise indices, as well as noise annoyance various indices, e.g. L_{10}, L_{eq} and OTNAI, and this again can be achieved by the comprehensive computer model UBSUB. The model utilises the prediction formulas which were reported in Chapters 7 and 8.

The independent variables of traffic noise in urban and suburban areas are always subject to change. This change without doubt has great influence on the level of propagated noise, which should not exceed specific limits as reported in section 4.5. Thus, in order to maintain the recommended noise level or to decrease the negative influence of any environmental change, it is beneficial to be able to examine the effects of the related variables individually. It is from this standpoint that the graphic computer model (GRUS) was established. The main advantage of such a model is that it is possible to operate a better environmental system by modifying any variable which causes a high level of noise (according to its degree of participation with other variables). The model utilises the prediction formulas which were reported in Chapter 7.

This chapter describes the development of UBSUB and GRUS models. It includes the following subjects.

(1) Computer model design
(2) Components, description, structure and validation of the UBSUB model.
(3) Procedures in the establishment of the graphic model GRUS.
(4) Practical application of the prediction models of this study

9.2 COMPUTER MODEL DESIGN

Before investigating the development of the computer models of this chapter it is useful to consider in general what is involving in solving a problem using a computer. There are five phases involved in designing a computer model (Balfour and Marwick, 1979). These are:

(1) Specify the problem
(2) Analyse the problem
(3) Design a method of solution for the problem
(4) Choice of a suitable programming language
(5) Test the model

The problem to be dealt with in this research is well specified in previous chapters. The problem is traffic noise exposure and noise annoyance in urban and suburban areas where the flow of traffic is non-free. The aim, therefore, was to establish prediction standards to be employed to minimise noise effects.

The analysis of the problem consists of collecting sufficient information on the subject of the study. It means determining what variables are involved in the solution, these having been already identified in previous chapters.

Designing a method of solution is the most difficult phase. The method must represent the real situation and work for all sets of data given to it in an efficient and satisfactory manner. Thus, the method behind the models of this chapter is based on the characteristics of everyday behaviour of vehicular transport. It also utilise the developed mathematical models (previous chapters) which were appropriate and accurate.

There are different types of programming languages which can be used in computer models.

(1) The special purpose language, e.g. MINITAB or Gino. The creation of the model in this case is restricted by the special characteristics of the language. This is normally suitable for particular goals, for example, MINITAB is useful for finding elements of regression analysis and Gino for plotting graphs. The users, therefore, are limited here by the nature of this type of programming. A special purpose programming language was used to develop the graphic model GRUS discussed in this chapter.

(2) The general purpose language, e.g. FORTRAN. In this case the user writes a programme appropriate to the subject of interest. The main advantage is the user's freedom to consider any components and conditions. When an engineer decides to use a computer to solve a given problem, and he does not have an adequate program already available, normally he selects FORTRAN language to program the problem solution. This is used worldwide. The programming language FORTAN 77 was used to establish the computer model UBSUB discussed in this chapter.

The forthcoming sections will describe the process of creation of the UBSUB and GRUS models.

9.3 COMPONENTS OF THE COMPUTER MODEL (UBSUB)

9.3.1 Independent variables

The model was designed for the handling of emitted road traffic noise which is a function of independent variables. Two types of variables were eventually used. These may be categorised as 'basic variables' and 'descriptive variables'.

The 'basic variables' are :

(1) Traffic system variables: i.e, L, M, H, Q, P and V
(2) Road system variables: i.e, W and J
(3) Building variables (propagation variables): i.e, d, K, N, F and HI.

The dependence of noise levels on the above variables has been examined in the preceding chapters.

The 'descriptive variables' are :

(1) Traffic system variables: i.e, traffic directions, accelerating and decelerating status of traffic and traffic conditions.
(2) Road system variables: i.e, number of lanes, condition of road surface and kind of junctions.
(3) Land use classification: i.e, residential, office, shopping, open space, urban main road or suburban principal route.
(4) Weather conditions: i.e, wet, dry or windy.

9.3.2 Dependent variables

These are most commonly used noise indices. L_{10}, L_{eq} dB(A), L_{50} and L_{90} have been included for the purpose of evaluation.

9.4 GENERAL DESCRIPTION OF UBSUB MODEL

The theory behind the model is based on the characteristics of the everyday behaviour of vehicular transport in urban and suburban contexts when the flow of traffic is interrupted by junctions. The operations of this mode of transportation are usually governed by traffic engineering methods, e.g. theory of traffic flow (Salter, 1976).

Road networks are considered as a series of nodes and connecting links (see Sections 3.3.1 and 5.4.2). In this situation, traffic noise is generated by a number of vehicles of different specifications being driven under changing conditions on various road layouts surrounded by buildings and areas of different land use. Noise level fluctuates with time and varies according to circumstances. For example, junctions often restrict the smooth flow of traffic because vehicles have to decelerate in the approach, stop, then cross the junction itself and finally accelerate away to cruising speed once again. This phenomenon causes changeable noise levels. Surrounding buildings which are sufficiently close to the side of the road networks also reflect back the sound of the road.

Noise levels from a stream of traffic, therefore, depend upon the operational characteristics of the traffic system, configuration of road networks, position of surrounding buildings and the classification of the adjacent area. The total level which is heard by the subjects in and around the buildings is a result of the combination and interaction of the above factors.

The model has been designed to consider the total noise level at each specific place as a function of the above mentioned interrelated factors. These factors, therefore, have been labelled 'basic variables' and 'descriptive variables' in order to cover them during the computer model procedure.

Vehicles in the traffic stream were classified as one of three kinds: light, medium or heavy (Chapter 5), while the mean speed of traffic passing the measurement position was taken into account. The mixture of these kinds of vehicles was considered as one noise source. Traffic conditions at each site were defined according to the proportion of each class of vehicles.

The width of roads as well as the junctions was identified. The junctions were considered as a reference position and traffic noise evaluated according to the distance between measurement site and the reference position along their arms. The UBSUB model assumes that the restricted flow imposed by various junction types influences the noise generated by vehicles over a specific distance. This is based on the fact that a vehicle accelerating from a stationary condition would produce a maximum noise level over this distance (see Chapter 6). Other variables which influence the level of noise are also defined by the model. These are the acceleration and deceleration of traffic and its direction. Each junction (node) and site were identified by number as a reference, and only level links were considered. The model was also designed to accommodate two, four or more lanes and the type of road surface. Whatever the number of lanes and their directions the model grouped them together as one roadway.

The propagation variables, e.g. building locations and the land use classification were also taken into account by the model. Three cases of weather conditions were covered.

Noise levels are computed to define the climate at each selected site, where total noise exposure at any point is a function of the considered variables. Fig 9.1 shows a typical measurement location and the variables covered by the model. The following expressions which were developed earlier were utilised to facilitate the computation (see Chapters 7 & 8).

(1) Eq. 7.1 - L_{10} dB(A), urban conditions.

(2) Eq. 7.3 - L_{eq} dB(A), urban conditions.

(3) Eq. 7.7 - L_{50} dB(A), urban conditions.

(4) Eq. 7.8 - L_{90} dB(A), urban conditions.

(5) Eq. 7.2 - L_{10} dB(A), suburban and urban conditions.

(6) Eq. 7.4 - L_{eq} dB(A), suburban and urban conditions.

(7) Eq. 7.9 - L_{50} dB(A), suburban and urban conditions.

(8) Eq. 7.10 - L_{90} dB(A), suburban and urban conditions.

(9) Eq. 7.6 - L_{eq} (l_x) dB(A), suburban and urban conditions.

To evaluate traffic noise annoyance, the following expressions were also utilised by the computer model:

(1) Eq. 8.1 - OTNAI (L_{10} dB(A))

(2) Eq. 8.2 - OTNAI (L_{eq} DB(A))

(3) Eq. 8.3 - OTNAI (L_{50} dB(A))

The model computes the above equations a number of times according to the required site numbers. The resulting output gives the predicted noise exposure values, predicted noise annoyance values and other expected characteristics of each site under consideration.

9.5 STRUCTURE OF THE MODEL

The computer model is written in standard FORTRAN 77 language and was run on a Honeywell computer with the Multics operating system at Bath University. Input data describing the independent variables of interest are required to perform various calculations. These variables were chosen for their importance, which emerged through the physical and social surveys (Chapters 6,7 and 8).

Input to the program consists of the measured data (e.g. 204 sites) which have to be arranged in a particular order. Thus, it was decided to group them in individual tables to arrange their numeric values. Each table indicates a block of data characterising particular information where each row corresponds to the measurements taken at a given site location. The model does not limit the number of sites. The input data tables are identified individually by five-letter code names: -trvar, trcha, rdvar, bdvar, lucla and wecon. See Tables 9.1 - 9.6.

1. TRAFFIC VARIABLES

SELECTED SITE NUMBERS = 1 5

Site No.	V	L	M	H	Q	P
1	26.65	2024.00	205.00	52.00	2281.00	11.30
2	38.96	2277.00	213.00	36.00	2526.00	9.86
3	24.00	257.00	10.00	0.00	267.00	3.75
4	36.70	483.00	21.00	0.00	504.00	4.17
5	11.50	544.00	44.00	0.00	588.00	7.48
6	24.40	260.00	14.00	0.00	274.00	5.11

V - Mean speed (km/h) L - Light vehicles (v/h)
M - Medium vehicles (v/h) H - Heavy vehicles (v/h)
P - Percentage of medium and heavy vehicles (%)
Q - Traffic flow (v/h)

Table 9.1 Input data file (trvar) of the computer model

2. TRAFFIC CHARACTERISTICS

Site No.	Traffic conditions			Traffic status		Traffic direction	
	Light	Medium	Heavy	Accel.	Decel.	One	Two
1	N	N	Y	Y	N	N	Y
2	N	N	Y	Y	N	N	Y
3	N	Y	N	Y	N	Y	N
4	N	Y	N	N	Y	N	Y
5	N	Y	N	Y	N	N	Y
6	N	Y	N	N	Y	Y	N

Y - Yes N - No

Table 9.2 Input data file (trcha) of the computer model

3a. ROAD VARIABLES

Site No.	W	No.of lanes			Road surface	
		Two	Four	More	Asphalt	Concrete
1	9.65	Y	N	N	Y	N
2	9.90	Y	N	N	Y	N
3	8.00	N	Y	N	Y	N
4	12.00	N	N	Y	Y	N
5	9.30	Y	N	N	Y	N
6	10.00	N	Y	N	Y	N

....contd

3b. ROAD VARIABLES

Site No.	J	Kind of junctions		
		TL	RB	PJ
1	25.00	Y	N	N
2	113.40	Y	N	N
3	50.00	N	N	N
4	238.00	N	N	Y
5	7.50	N	Y	N
6	4.60	N	Y	N

W - Road width (m)   J - Distance from junction (m)
TL - Traffic light   RB - Roundabout
PJ - Priority junction   N - No
Y - Yes

Table 9.3 Input data file (rdvar) of the computer model

4. BUILDING VARIABLES

Site No.	d	F	HI	K	SR
1	2.10	13.00	1.20	1.00	3.00
2	5.40	16.00	1.20	1.00	7.00
3	3.60	13.00	1.20	1.00	104.00
4	2.00	14.80	1.20	1.00	110.00
5	4.70	12.60	1.20	1.00	82.00
6	2.70	13.50	1.20	1.00	70.00

d - Distance from nearside facade (m)
F - Distance from farside facade (m)
HI - Height of measurement (m)
K - Distance between measurement point
and nearside kerb (m)
SR - Site reference

Table 9.4 Input data file (bdvar) of the computer model

5. LAND USE CLASSIFICATION

Site NO.	RS	O	S	OS	UMR	SPR
1	N	N	N	N	Y	N
2	N	N	N	N	Y	N
3	N	N	Y	N	N	N
4	Y	N	N	N	N	N
5	N	Y	N	N	N	N
6	N	Y	N	N	N	N

RS - Residential
O - Office
S - Shopping
OS - Open space
UMR - Urban main road
SPR - Suburban principal route
Y - Yes
N - No

Table 9.5 Input data file (lucla) of the computer model

6. WEATHER CONDITIONS

Site No.	Wet	Dry	Windy
1	N	Y	N
2	N	Y	N
3	N	Y	N
4	N	Y	N
5	N	Y	N
6	N	Y	N

Y - Yes
N - No

Table 9.6 Input data file (wecon) of the computer model

The code names are useful while accessing the exterior stored data. The information stored in all the tables is formatted explicitly so that channelling of data to a designated array becomes straightforward and precise. For example, in Table 9.1 'Selected site numbers' are shown with two specific numbers separated by a blank. These two numbers represent the range of sites for which various calculations are required. The site numbers have to be entered as integers because of the type of format definition used in the main program. The complete description of the formatting of the tables follows next.

9.5.1 Description of the data tables

As indicated above, there are six data tables. In Table 9.1 (trvar) traffic variables are entered. The column representing site numbers has integer numerics, since these numbers are used merely for tabulating the data corresponding to each location. However, they can be entered as even real values. An important thing to remember is the field width, which in this case is six characters beginning from the furthest left digit in the table. That is, the site numbers can be typed anywhere inside this field. This field may contain blank characters, which can be ignored.

The second and subsequent columns have ten character field width and the values are real and right-justified. The number of digits in the fractional part of the real numbers has to be two, again because of the type of format declaration used in the main program.

In the table code-named 'trcha', the letters 'Y' and 'N' represent 'Yes' and 'No' respectively. They are the conditions prevailing at the time of measurement. The model has been written to count the number of times the letters 'Y' and 'N' appear within the selected site numbers and below a particular column.

The table 'rdvar' shows road variables such as W and J under different measurement conditions. The numbers have to be right-justified. The number of digits in the fractional part again has to be two. Also, the columns corresponding to the letters 'Y' and 'N' are equally spaced.

In table 'bdvar' values of the variables describing building considerations are entered at various site numbers. The widths between the consecutive real numbers are the same as those given in table 'trvar'.

The arrangement of variables and measurement conditions in other input tables follows the same pattern as in those which have been discussed so far. Hence further explanation is not given here. Instead, in the section immediately below, a detailed description of the model has been presented.

9.5.2 Description of the program

A knowledge of how the program operates in this work will help the user to tabulate the measured results for various sites.

Measured data is fed to several arrays in the program. The arrays which were particularly used for this purpose are predefined in a two by two matrix with a maximum 2000 by 2000 as the array dimensions. This means that the model can assess a maximum 2000 sites under each run. However, in the event of higher site numbers the user should change the 2000x2000 to the required range. The following extract explains the program's internal performance.

```
open (55, file = 'trvar', form = 'formatted', mode = 'inout')
read (55,1) pk1, pk2, min, nsite
do 3 k = 1, nsite
read (55,12) npsit(k), ((dat12 (i,J), i = 1,6), J = k,k)
3  continue
1  format (//2a8, 2i3//)
12  format (i6, 2x, 6f10.2)
close (55)
```

Here the first line, namely the 'open' statement, is used to connect the formated table 'trvar'. The second statement inputs the minimum and maximum values of specified site numbers. Since all the variables are predefined in double precision, the field width for a format in line number 6 above is used as equal to 8. This identity is retained throughout the process of inputting the literal data.

In line number 4 above, several values of the variables are read from the same table 'trvar' according to format f10.2. The 'do' loop permits the read statement to be executed as many times as the site numbers are in the table. The first looping for the array dat12 inputs the number of variables present in the table, whereas the second one is used to read these variables for different site numbers. The limit of this second looping therefore depends on the number of sites under consideration. Even though it is necessary to calculate and tabulate the noise levels within the boundaries of the already available site numbers (the variable 'min' in line 2, above, has stored minimum site numbers), for convenience the whole table is read. Later, the calculations are restricted to the selected site numbers.

The last statement 'close (55)' is used to end the reading process of table 'trvar'.

The technique used to read and store remaining tables follows the same pattern as that discussed above.

The calculation of L_{10}, L_{50}, L_{90}, L_{eq} and $L_{eq}(l_x)$ is straightforward. Two subroutines mainly 'suburban' and 'urban' are called each time to determine the noise levels respectively for suburban and urban locations. The results are stored in several one dimensional arrays. The mean values of the noise levels are then calculated in the usual way as shown in the program.

To select the minimum and maximum values of the parameters, a subroutine called 'great' is used. The one dimensional array used in this subroutine corresponds to one particular parameter at different site locations. All the elements of the array are compared one by one and then arranged in ascending order. These numbers are then stored again in the same array so as to use them in the main program. After executing this 'call great (....' statement, the array will contain parameter values such that the user can pin-point minimum and maximum values. Now, when an output of the result is required, the first element in the array is listed below the title 'MINIMUM', whereas the last one is under the title 'MAXIMUM'.

In order to count the number of 'Y's' and 'N's' in columns corresponding to the conditions prevailing at the time of measurement, another subroutine called 'count' is executed. In this subroutine the number of 'Y's and 'N's are counted by using the following control statements:

```
if (aa(i). eq. '          Y') go to 2
if (aa(i). eq. '          N') go to 3
```

There are several blanks associated with 'Y' or 'N' and each element of the array 'aa' contains seven blanks as well as either 'Y' or 'N'. The count statements $K_N = K_N + 1$ and $K_Y = K_Y + 1$ store the number of 'N's' and 'Y's' respectively after completing the execution of the subroutine.

The printed output file consists of the listing of the various values calculated above. Table 9.7 is given as an example of the typical output for site numbers between 1 and 5. In the listings of the number of counts of the conditions prevailing at the time of measurement, all '0's indicate the absence of those particular conditions. That means only 'Y's were present within the selected site numbers under a particular column specifying the measurement conditions. Figure 9.2 shows a flow chart of the computational sequency used in the UBSUB model.

9.5.3 Output report

The UBSUB output is in the form of a printed report consisting of 7 tables as follows (see Tables 9.7):

Table 1. Suburban and Urban conditions

This table consists of two parts as follows:

(a) It presents predicted noise levels, L_{10}, L_{50}, L_{90}, L_{eq} and $L_{eq}(l_x)$ (Eq.7.6), with regard to the elements of the 'Urban and Suburban Models' besides the 'descriptive variables'. This output is usually necessary when the speed of traffic ranges from 10 to 75 km/h and Q is more significant than traffic composition. In these conditions, especially when the speed is above 50 km/h, the accelerating and maneuvering of vehicles are less than in the case of Table 2.

(b) This table is also designed to include predicted noise annoyance values. It gives OTNAI in terms of L_{10}, L_{eq} and L_{50}.

Table 2. Urban conditions

This table consists of two parts as follows:

(a) It contains predicted noise levels L_{10}, L_{50}, L_{90} and L_{eq} in terms of the elements of the 'Urban Models', in addition to the 'descriptive variables'. This output is required for conditions where speeds below 48 km/h and traffic composition (3 classes of vehicles) affect the environment significantly. At those speeds, accelerating and maneuvering of vehicles are predominant. The noise associated with these phenomena consists of peak levels and its magnitude is subject to the proportion of each kind of vehicle in the traffic stream.

(b) This table also contains predicted noise annoyance. The values of the Overall Traffic Noise Annoyance Index (OTNAI) are presented in terms of L_{10}, L_{eq} and L_{50}.

Table 3. Mean values of the independent variables.

This table contains the mean values of: Q, L, M, H and V.

Table 4. Mean values of the predicted noise levels and noise annoyance.

This table gives the means of obtained values in Tables 1 and 2.

Table 5. Range of independent variables.

This table gives the range of the variables: Q, L, M, H, V, W, F, J, d and P.

Table 6. Range of predicted noise levels and noise annoyance.

This table represents the range of values obtained in Tables 1 and 2 are given here.

Table 7. Description of measurement locations.

This table identifies height of measurements; distance between measurement points and nearside kerb; the traffic conditions; accelerating and decelerating of traffic; traffic directions; number of lanes; road surface conditions; kind of junctions, land use classification and weather conditions.

Table 9.7 Typical output of UBSUB model

Total site Nos = 5

1. URBAN AND SUBURBAN CONDITIONS

(a) Predicted noise levels

Site No.	L10	L50	L90	Leq	Leq(lx)
1	83.44	77.77	72.00	80.52	80.27
2	79.77	73.88	67.94	76.77	76.68
3	70.53	63.16	55.87	67.55	67.53
4	71.42	64.32	57.38	68.43	68.38
5	77.18	69.90	62.75	74.38	73.95

* Lx=a0-a1*log(V)+a2*log(Q)+a3*P-a4*log(F)-a5*J-a6*log(N)

Leq(lx) = 0.968L50+0.436(L10-L90)

(b) Predicted traffic noise annoyance

Site No.	OTNAI(L10)	OTNAI(Leq)	OTNAI(L50)
1	1.84	1.80	1.90
2	2.00	1.95	2.07
3	3.01	2.98	2.90
4	3.46	3.39	3.50
5	4.10	4.04	4.08

* OTNAI=Overall Traffic Noise Annoyance Index

=a0(Lx)-a1

... contd

2. URBAN CONDITIONS

(a) Predicted noise levels

Site No.	L10	L50	L90	Leq
1	84.42	74.93	68.63	81.52
2	79.84	70.30	64.13	76.87
3	70.33	59.20	51.49	67.44
4	71.94	60.64	52.99	69.03
5	76.79	65.90	58.43	74.05

* Lx=a0-a1*log(V)+a2*log(L+6M+10H)-a3*log(F)-a4*J-a5*log(d-k)

(b) Predicted traffic noise annoyance

Site No.	OTNAI(L10)	OTNAI(Leq)	OTNAI(L50)
1	1.81	4.21	1.31
2	2.09	3.41	1.53
3	2.94	1.78	2.31
4	3.47	2.05	2.97
5	4.27	2.92	3.66

3. MEAN VALUES OF THE INDEPENDENT VARIABLES

V = 27.5620km/h   L = 1117.0000 v/h

M = 98.6000 v/h   H = 17.6000 v/h

Q = 1233.2000 v/h

... contd

4. MEAN VALUES OF THE PREDICTED NOISE LEVELS AND NOISE ANNOYANCE

(a) For Suburban and Urban Conditions

L10= 76.4676dB(A) L50= 69.8055dB(A)
L90= 63.1871dB(A) Leq= 73.5306dB(A)
Leq(Lx)= 73.3620dB(A)
OTNAI(L10)= 14.4091 OTNAI(Leq)= 14.1540
OTNAI(L50)= 14.4551

(b) For Urban Conditions

L10= 76.6649dB(A) L50= 66.1948dB(A)
L90= 59.1330dB(A) Leq= 73.7805dB(A)
OTNAI(L10)= 14.5818 OTNAI(Leq)= 14.3701
OTNAI(L50)= 11.7651

5. RANGE OF INDEPENDENT VARIABLES

VARIABLE	MAXIMUM	MINIMUM
V	38.96	11.50
L	2277.00	257.00
M	213.00	10.00
H	52.00	0.00
W	12.00	8.00
d	5.40	2.00
J	238.00	7.50
Q	2526.00	267.00
P	11.30	3.75
F	16.00	12.60

... contd

6. RANGE OF PREDICTED NOISE LEVELS AND NOISE ANNOYANCE

(a) For Suburban and Urban Conditions

INDEX	MAXIMUM	MINIMUM
L10	83.44	70.53
L50	77.77	63.16
L90	72.00	55.87
Leq	80.52	67.55
Leq(Lx)	80.27	67.53
OTNAI(L10)	4.10	1.84
OTNAI(Leq)	4.04	1.80
OTNAI(L50)	4.08	1.90

(b) For Urban Conditions

INDEX	MAXIMUM	MINIMUM
L10	84.42	70.33
L50	74.93	59.20
L90	68.63	51.49
Leq	81.52	67.44
OTNAI(L10)	4.27	1.81
OTNAI(Leq)	2.92	4.21
OTNAI(L50)	3.66	1.31

... contd

7. DISTRIBUTION OF MEASUREMENT LOCATIONS

Height of Measurement Point= 1.20

Distance Between Measurement Point and Nearside Kerb= 1.00

No. of Light Traffic Sites= 0

No. of Medium Traffic Sites= 3

No. of Heavy Traffic Sites= 2

No. of Accelerating Traffic Sites= 4

No. of Decelerating Traffic Sites= 1

No. of One Way Traffic Sites= 1

No. of Two Way Traffic Sites= 4

No. of Two Lane Sites= 3

No. of Four Lane Sites= 1

No. of More Lane Sites= 1

No. of Asphalt Road Surface Sites= 5

No. of Concrete Road Surface Sites= 0

No. of Traffic Light Intersections= 2

No. of Roundabouts= 1

No. of Priority Junctions= 1

No. of Residential Area Sites= 1

No. of Office Area Sites= 1

No. of Shopping Area Sites= 1

No. of Open Space Area Sites= 0

No. of Urban Main Road Sites= 2

No. of Suburban Principal Route Sites= 0

No. of Wet Weather Sites= 0

No. of Dry Weather Sites= 5

No. of Windy Weather Sites= 0

9.6 VALIDATION OF UBSUB MODEL

Validation of any system is not an easy task since there are no common criteria which can be used to define the validity. Thus, researchers have established various methods of testing. It has become generally accepted that the valid model should behave in a manner similar to the underlying phenomenon in order to determine whether it actually does represent the phenomenon it is supposed to represent. This is achieved by comparing the output from the model with known data from the real world. However, direct comparison with previous models is not easy since there are no studies which have systematically considered all of the components and conditions involved in establishing the UBSUB model.

A comparison of the measured noise level values at the 204 urban and suburban sites with those predicted by the model shows the high efficiency of the model as a representation of the real situation. The difference between measured and predicted L_{10} was ± 1.8 dB(A) while for L_{eq} the difference was ± 2 dB(A).

In order to operate a further check of validity, data from eight new sites were compared with the predicted values using the model. The characteristics of the new sites are illustrated in Table 9.8. The values of F ranged from 9.4 to 13.5 and N from 1 to 2.8m. The distance from the selected junctions was between 25 and 200 m. All the sites were on the accelerating side of traffic. Six measurements were carried out at each site, three between 10.00 am and 12.00 midday and three between 15.00 and 17.00 hours. The period during which samples were taken was restricted to six hours in order to test the performance of the model where the peak noise levels appear in many areas at the same time every day. The sites varied with regard to traffic composition (0 - 13%) and speeds (16 - 59 km/h), while the range of L_{10} was found to be from 69.4 to 84 dB(A). The model gave accuracy with $\pm$ 1.7 dB(A). Table 9.9 illustrates measured values and values predicted by the model.

Site no.	Position	Land use	Junction
1D	Gloucester Road	suburban	TL
2D	Newbridge Hill	suburban	TL
3D	Lower Bristol Road	urban main road	TL
4D	Brook Road	urban main road	TL
5D	Bridge Road	residential	PJ
6D	Moorland Road	shopping	PJ
7D	Brock Street	residential	RB
8D	Lower Oldfield Park	residential	PJ

Table 9.8 Characteristics of new sites

Site no.	Measured L_{10} dB(A)	Predicted L_{10} dB(A)	Residual (mes.-pred.) dB(A)
1D	84	82.30	1.70
2D	79.9	79.10	0.80
3D	81.2	82.40	-1.20
4D	77.5	78.41	-0.91
5D	73.5	72.42	1.08
6D	74.1	74.69	-0.59
7D	69.3	70.92	-1.62
8D	75.9	75.57	0.33

Table 9.9 Comparison of measured L_{10} and values predicted by the computer model (8 new positions)

The new UBSUB is a comprehensive model that consider all the common dependent and independent components of urban and suburban environments. This computerised system was created to help engineers and planners search for large quantities of information. The model has been kept as simple as possible bearing in mind efficiency and usefulness. In practical use, the model can easily provide rich assessment of any specific place of interest. For example, the following steps can be taken: the city can be divided into sections according to its Land Use classifications. Then a list of references can be issued in the form of numbers for each section of the road network. To run the model the only requirement here is to enter the input data which comprise a variety of conditions. By entering simple commands such as 1 5 in Table 9.1, the user can obtain detailed information on the sites 1 to 5 based on various indices and characteristics as described in Table 9.7. As well as the computer terminal, the user may need a printer for convenience.

The model has another advantage since the input data includes changeable (e.g. speed) and unchangeable (e.g residential area) natures. This gives the model the benefit of reducing the expense and time spent collecting the data. Thus, the UBSUB employs a computer in environmental noise control to serve as a tool for various purposes. It satisfies the engineers who plan, design, construct and operate facilities in built-up areas in order to attain objectives useful to society.

In view of the lack of information concerning many variables and the unavailability of a comprehensive prediction method, the UBSUB has several advantages. Firstly, it is able to generate a large amount of necessary data which enables trends in noise levels and built-up features to be investigated. Secondly, it can also cater for a wider range of input and output variables than previous studies, and almost all the planning and design factors can be appraised. Thirdly, the environmental features of urban and suburban situations are subject to change from time to time and the model has the flexibility to incorporate these variations. Fourthly, the model is written in a common computer language and it could be run on or translated to any system. Figures 9.3 - 9.4 show a comparison between measured noise level values and the values calculated by the UBSUB model.

9.7 GRAPHIC COMPUTER MODEL (GRUS)

9.7.1 Objective

In order to maintain the recommended environmental climate, the effects of variables need to be estimated individually. The main advantage is to modify the variables responsible for the high noise level. For example, the separation of light and heavy traffic to decrease the traffic flow on specific roads will minimise the level of propagated noise in the area. This section, therefore, deals with the development of a graphic computer model capable of evaluating graphically the effect on the noise level (i.e L_{10} and L_{eq} dB(A)) of any individual variable in terms of its interaction with other elements. The model permits one to assess the expected noise level under urban and suburban conditions, and a wide range of probabilities.

9.7.2 Structure of the Model

The following prediction models derived earlier for both urban and suburban situations are being used by GRUS to quantify the noise information.

(1) L_{10} model for urban conditions in terms of road width (W). This model was developed at an early stage in this study. But it was modified later and introduced in the form of Equation 7.1 as W was replaced by F. However, it was decided to include this model here in case the assessment of noise in connection with W is required.

$$L_{110}=54.8-5.75\log_{10}V-4.10\log_{10}W-0.0116J$$
$$+\log_{10}(L+6M+10H)-5.26\log_{10}(d-K) \quad \ldots (9.1)$$

(2) Eq.7.1 - L_{10} dB(A), urban conditions

(3) Eq.7.3 - L_{eq} dB(A), urban conditions

(4) Eq.7.2 - L_{10} dB(A), urban and suburban conditions

(5) Eq,7.4 - L_{eq} dB(A), urban and suburban conditions

A computer program was developed utilising the Gino graphics facilities (CADCL, 1983) on a Honeywell system to plot predicted noise values against various elements. As the noise level at a given point is affected by several variables, it is not possible to observe all their effects under varying conditions in one plot. Therefore, to organise the investigation effectively, each variable is examined independently, while keeping others at specific values. For example, in the L_{10} against V plot, it was possible to plot several curves (see Fig 9.5). Each of them have independent component limits such that

(1) L_{10} against V with L, M, H, W, J and d values set at their minimum

(2) L_{10} against V with L, M H, W, J and d values set at their minimum.

(3) L_{10} against V with L at the maximum value and the rest of the parameters at minimum values.

(4) L_{10} against V with M at the maximum value and the rest of the parameters at minimum values..... and so on.

Thus, the model provides the user with a wide range of options. Selection of the best scheme depends on the objective of the investigation.

For convenience, only some of the output figures are discussed as an example in the following sections, because the program deals with a large amount of data. The noise levels were obtained within the range of the maximum and minimum values of the governing variables. The extreme values of these variables were based on the results of the aforementioned physical measurements of this study (Chapters 6 and 7). The information accumulated from these figures describes briefly the effect on traffic noise of each particular variable, under various probabilities. Urban conditions are dealt with (Eq.9.1) followed by suburban and urban conditions (Eq.7.3).

9.7.3 Effect of traffic speed, (V)

Figure 9.5 represents the predicted noise values against traffic speed variation. The predicted values were obtained using the graphic model mentioned above for urban conditions. The interpretation of the results is fairly straightforward.

The highest level of noise occurs when the speed is at a minimum value. The noise value decreases from there on, apparently reaching a minimum value at the maximum speed limit (48 km/h). It can also be seen that the number of vehicles has a significant influence on noise. Furthermore the junction distance, road width and facade distance when selected at their maximum values show a considerable decrease in noise. Apart from this, another important observation is with regard to the decrease in the L_{10} values as the speed changes from the indicated minimum to maximum. This is common between all of the curves shown in Figure 9.5. It is also clear from the figure that the L_{10} trend is not quite the same for the variation in the number of L, M and H, as the other variables. This is discussed below by highlighting noise variation, within the boundaries of these components.

9.7.4 Effect of number of vehicles (L, M and H)

Figure 9.6 is plotted to show the predicted noise values associated with the number of light vehicles. Several observations may be drawn from the variation of L_{10} as follows:

(1) The noise increase is quite rapid for L between 250 and 1450, and thereafter a roughly steady increase is observed.

(2) The increase in noise with increases in independent variables such as d, J and W is more or less steady. However, the steady pattern is disturbed by the number of heavy vehicles as seen in Fig 9.6. For example, L_{10} at L=250 for H set at its maximum value, equal to 84 dB(A). The same for H at the minimum value is equal to 76 dB(A). This reflects that there is an increase of 8 dB(A) simply when the number of heavy vehicles is increased from minimum to maximum level. On the other hand, there is no such large increase when the number of light vehicles is maximised. For example, when L=2950. In this case, when L=2950 and H at its maximum value, L_{10} is equal to about 90 dB(A). Meanwhile when

L=2950 and H at its minimum level, L_{10} is equal to about 88 dB(A). This difference (2dB(A)) is in fact four times less than that when L is equal to 250 (v/h). So this finding implies that the impact of the number of heavy vehicles on the noise level in urban areas is more than the medium and light vehicles.

The relationships between noise levels and numbers of medium and heavy vehicles are given in figure 9.7 and 9.8.

9.7.5 Effect of the road width, (W)

Figure 9.9 again displays similar characteristics to those of the L_{10} variations, but, here the x-axis is chosen to be for W. The predicted noise level has clear variation between W=16 and W=6m. The attenuation in noise level is quite steady over the 16m road width.

9.7.6 Effect of distance, (d and J)

Distance is one of the factors having the highest effect on the noise level. Figures 9.10 and 9.11 show the attenuation levels in noise with distances J and d where one of the distances, d, corresponds to that from the nearside of the building facade and the other one, J is from junctions.

The relationship between L_{10} and J, as predicted by the models, is linear. The attenuation is obvious and it depends on the effect of several other parameters as discussed earlier.

The above investigation describing the effect on noise by various elements in urban areas is also found to be applicable to suburban conditions. It has been found that the common variables of suburban and urban models have a similar effect on noise level. Traffic flow and percentage of medium and heavy vehicles which were not present in the previous discussion, have been considered below.

9.7.7 Effect of traffic flow (Q)

Figure 9.12 illustrates the effect of Q on L_{10}. As expected, the predicted values are highest for the highest percentile number of vehicles. For example, the increase in Q from 250 to 2950 (v/h), when all the variables are at their minimum levels, has maximised the predicted L_{10} by about 14 dB(A). Also the effect of P at its maximum value is obvious.

Figure 9.13 illustrates the comparison between the predicted noise level and percentage of medium and heavy vehicles. L_{eq} also has been found to follow a similar trend to that shown by L_{10}, in various situations, see Figures 9.14 - 9.15.

9.8 VALIDATION OF GRUS MODEL

The GRUS model permits the graphic evaluation of the predicted noise levels L_{10} and L_{eq} dB(A) under a variety of urban and suburban conditions. It deals with the influence of each of the 'basic variables' on the level of noise according to its degree of participation with the others. The model covers the main variables commonly used.

The GRUS was designed to estimate 170 probabilities at each run associated with 26 figures. It is easy to operate and based on reliable mathematical formulas. The only required input data to the model, by the user, are the maximum and minimum values of the basic variables under study. The model relies on a commonly-used programming language, so it can be utilised widely. It is also easy to modify.

In summary, the GRUS model can be practically employed to maintain an appropriate environmental noise climate, as well as to compare various strategies, by modifying any of the contributing variables.

9.9 APPLICATION OF THE PREDICTION MODELS OF THIS STUDY

Various prediction models have been established by this study. This section presents a brief description of their practical applications.

The models can be considered to fall into two families, 'simplified models' and 'detailed models'.

9.9.1 'Simplified models'

This family includes equations numbered 7.1 to 7.4, 7.6 to 7.10 & 8.1 to 8.3. The models can provide a rapid prediction of the anticipated level of noise in terms of 'basic variables'. Such evaluation is needed at some planning stages. For example, at the stage of long-term transportation planning (Section 3.4.2) it is necessary to have a general opinion about the environmental influence of a scheme on the surrounding area without considering details. The models are simple and easy to use manually. Furthermore, they are based on available or easily obtainable data. These are either from statistics such as a count of road traffic or from an ordinary map of the area such as the location of junctions. Decision-makers with everyday requirements can use these models for preliminary evaluation, e.g. quick evaluation of new building sites.

The models also provide a useful tool for assessing subjective response.

To summarise, the simplified models aid in rapid assessment and early planning and design operations.

9.9.2 'Detailed models'

This family includes the computer model UBSUB and the graphic computer model GRUS.

Detailed information is usually needed by planners and designers when a thorough project has been decided upon. At the stage of road design, for example, (Section 3.4.2), detailed information on each section of road is necessary. This allows a precise environmental policy to be established. The execution of traffic management schemes or urban planning (Sections 3.4.4 and 3.4.5) also demands detailed information on the road networks under consideration. Selection of a new hospital site, for example, needs an area which has an acceptable noise environment. This is achieved by carefully examining the land adjacent to the proposed site as well as the operational characteristics of the transportation system. Thus, information should be available which is sufficient to prepare an environmental noise-map of the area. To ensure that a planned residential development has an acceptable noise environment, attention should be given to the assessment of heavy lorry operations, and to future development, especially regarding the reflection of noise between buildings, the position of junctions and status of acceleration and deceleration of traffic. To summarise, the computer model will assist in preparing an environmental noise-map of an area with a variety of conditions, while the graphic model will aid in the modification of the individual variables in order to maintain the best alternative scheme.

9.10 SUMMARY

This chapter has dealt with establishment of a computer model (UBSUB) to assess and predict traffic noise and annoyance in complex built-up areas. This was necessary due to the unavailability of a comprehensive tool. The UBSUB allows the effects of variables in a wide range of conditions in urban and suburban areas to be considered.

The UBSUB predicts noise levels in terms of any of the well-used environmental noise indices, i.e L_{10}, L_{50}, L_{90} and L_{eq} dB(A) associated with traffic flow and speed, vehicle types, traffic characteristics, road layout, type of junctions, building structures, land use and weather conditions. The model was also designed to predict traffic noise annoyance (OTNAI) in terms of L_{10}, L_{eq} and L_{50}. UBSUB was designed to consider variables which characterise the structure of built-up areas, influence environmental noise and are necessary at the planning and design stages.

The model utilises empirical formulas which were developed during the course of the study and showed high accuracy. It makes a detailed assessment using all the necessary variables, and is designed to examine any large number of sites (e.g. 2000 sites) in each run. The UBSUB has been built to be as comprehensive a model as possible so that it can be utilised in different studies and can be further developed in future. It has been shown that the UBSUB model is reliable and capable of predicting noise levels with a high degree of accuracy ($\pm$ 1.8 dB(A)), appropriate to the design and planning process.

A graphic computer model GRUS to estimate the effects of independent variables on noise characteristics, L_{10} and L_{eq}, has been developed. It also utilises the developed prediction techniques. The graphic model GRUS is capable of identifying the variables that contribute to excessive noise levels, in order to enable the appropriate environmental policy to be chosen.

The practical applications of models in this study have been reported. The models can be considered to fall into two families 'simplified models' and 'detailed models'. The simplified models can provide a rapid prediction of the anticipated level of noise in terms of 'basic variables'. Decision-makers can use these models for preliminary evaluation. The 'detailed models' enable noise level values to be obtained in terms of a large number of variables. They provide a comprehensive and detailed method. This enables a convenient environmental policy to be established, which includes transportation planning, road building, traffic management, urban planning and building construction.

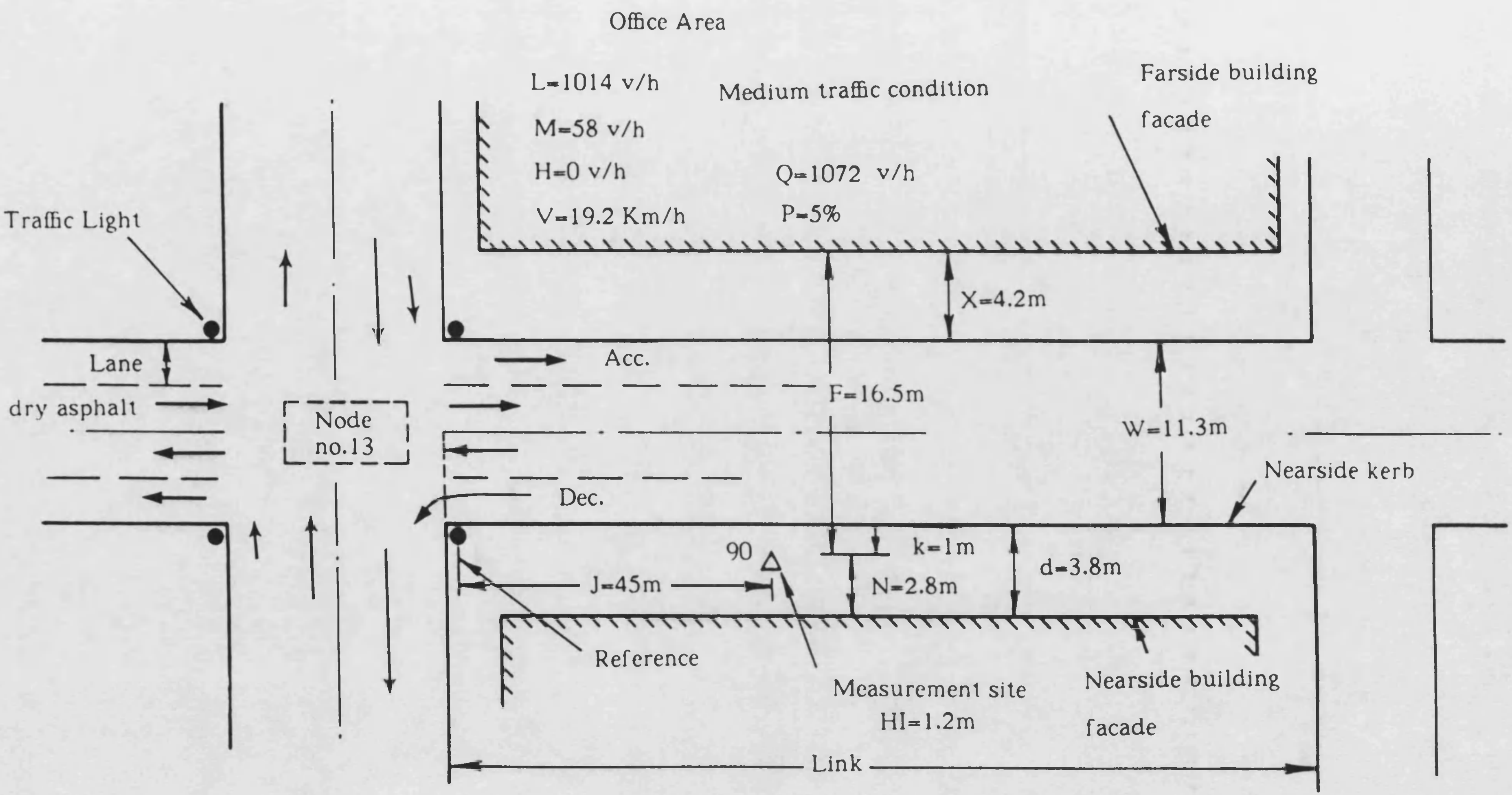
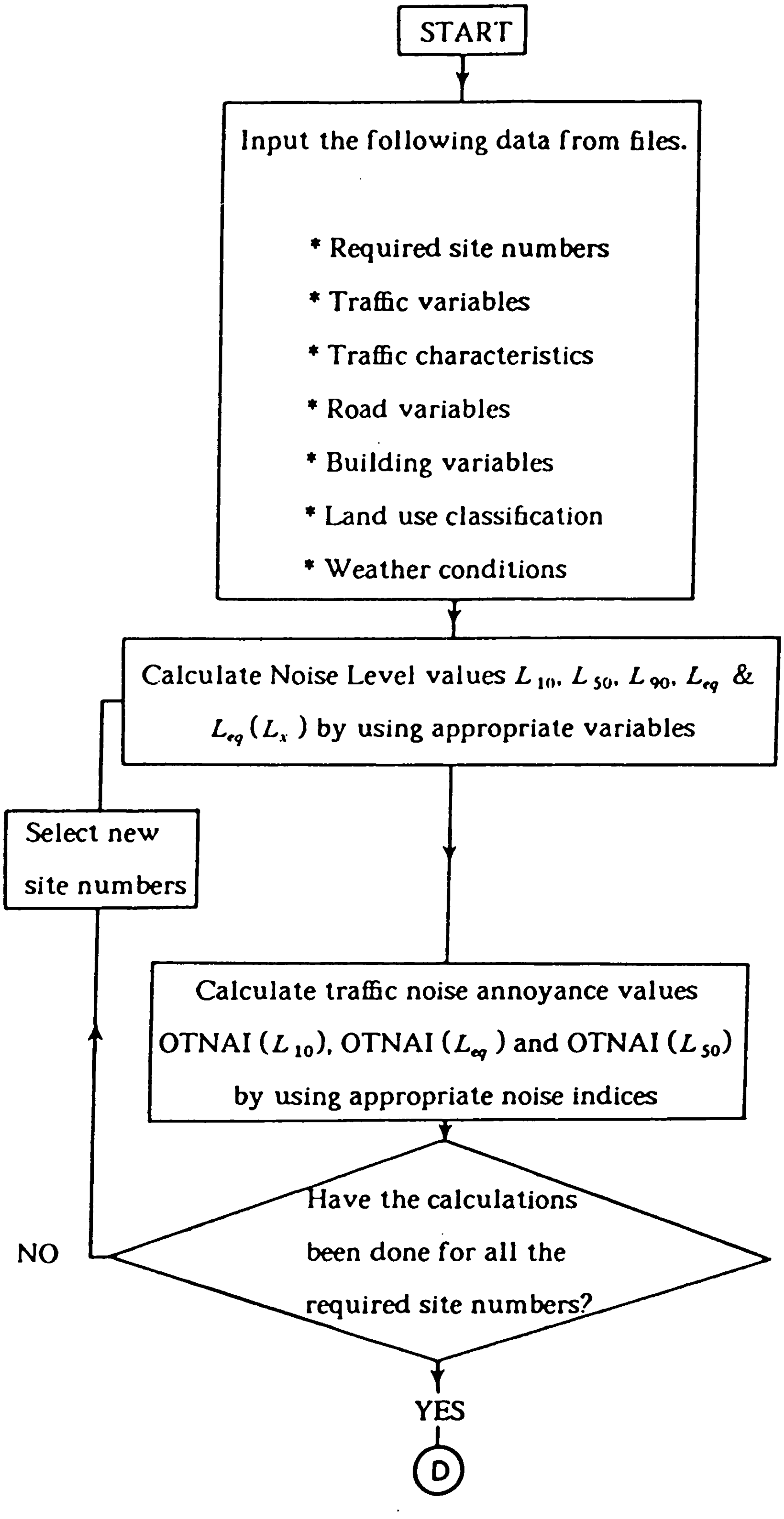


Fig 9.1 Typical measurement site and the variables covered by the computer model UBSUB


START
Input the following data from files.
* Required site numbers
* Traffic variables
* Traffic characteristics
* Road variables
* Building variables
* Land use classification
* Weather conditions
Calculate Noise Level values L_{10}, L_{50}, L_{90}, L_{eq} & $L_{eq}(L_x)$ by using appropriate variables
Select new site numbers
Calculate traffic noise annoyance values OTNAI (L_{10}), OTNAI (L_{eq}) and OTNAI (L_{50}) by using appropriate noise indices
Have the calculations been done for all the required site numbers?
NO
YES
D

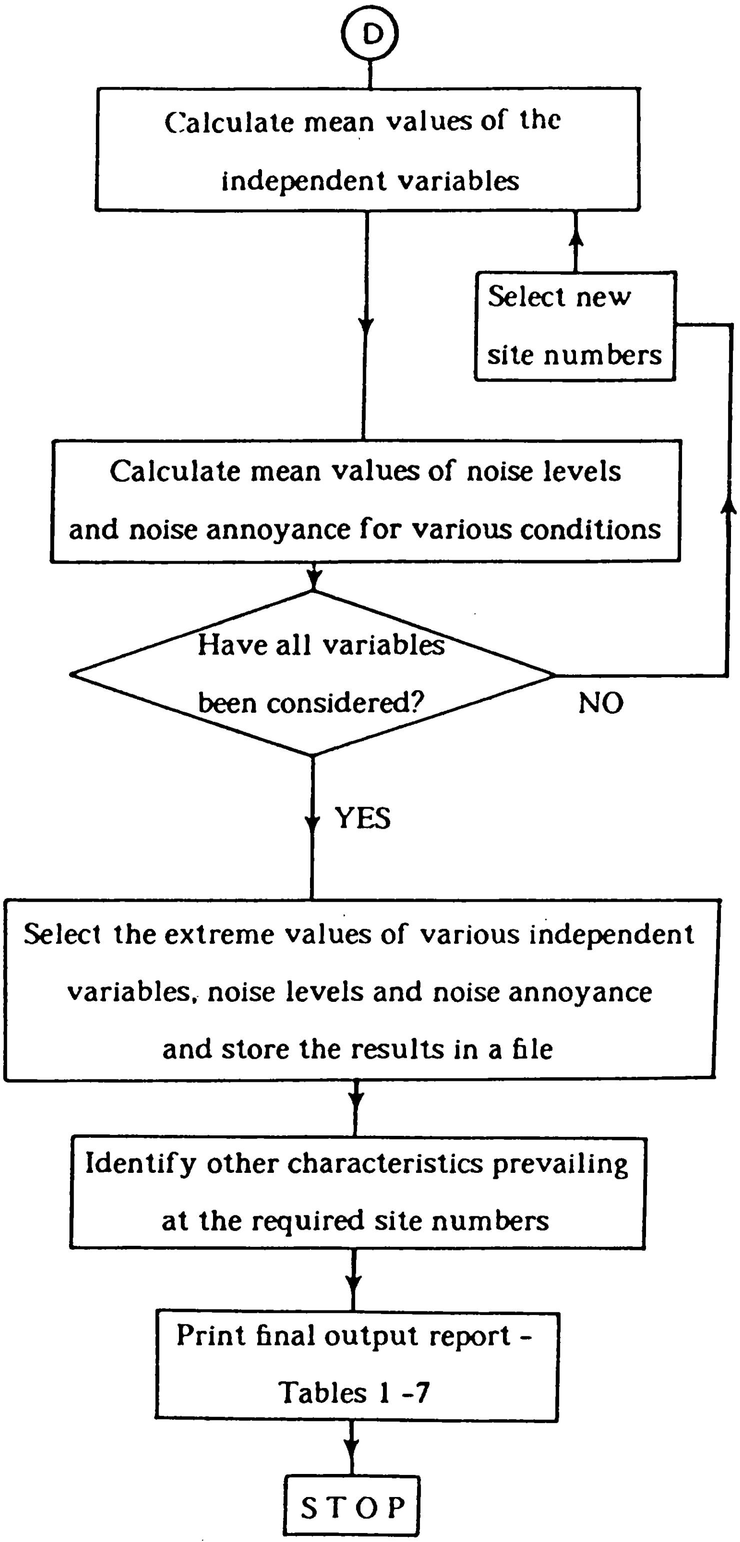


Fig 9.2 Flow chart of the computational sequence used in the UBSUB model

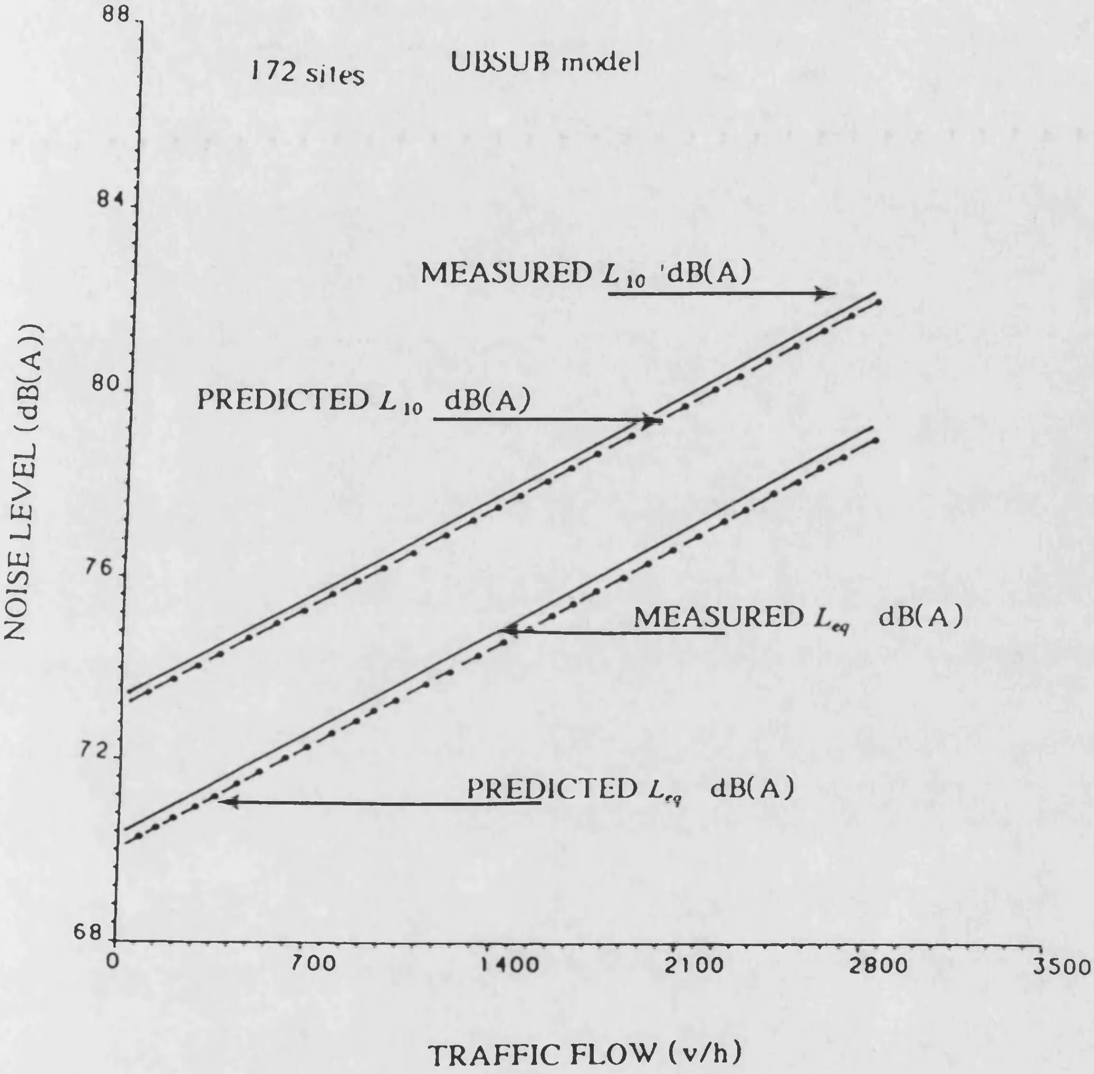


Fig 9.3 Comparison between noise level values and values predicted by the computer model for urban conditions

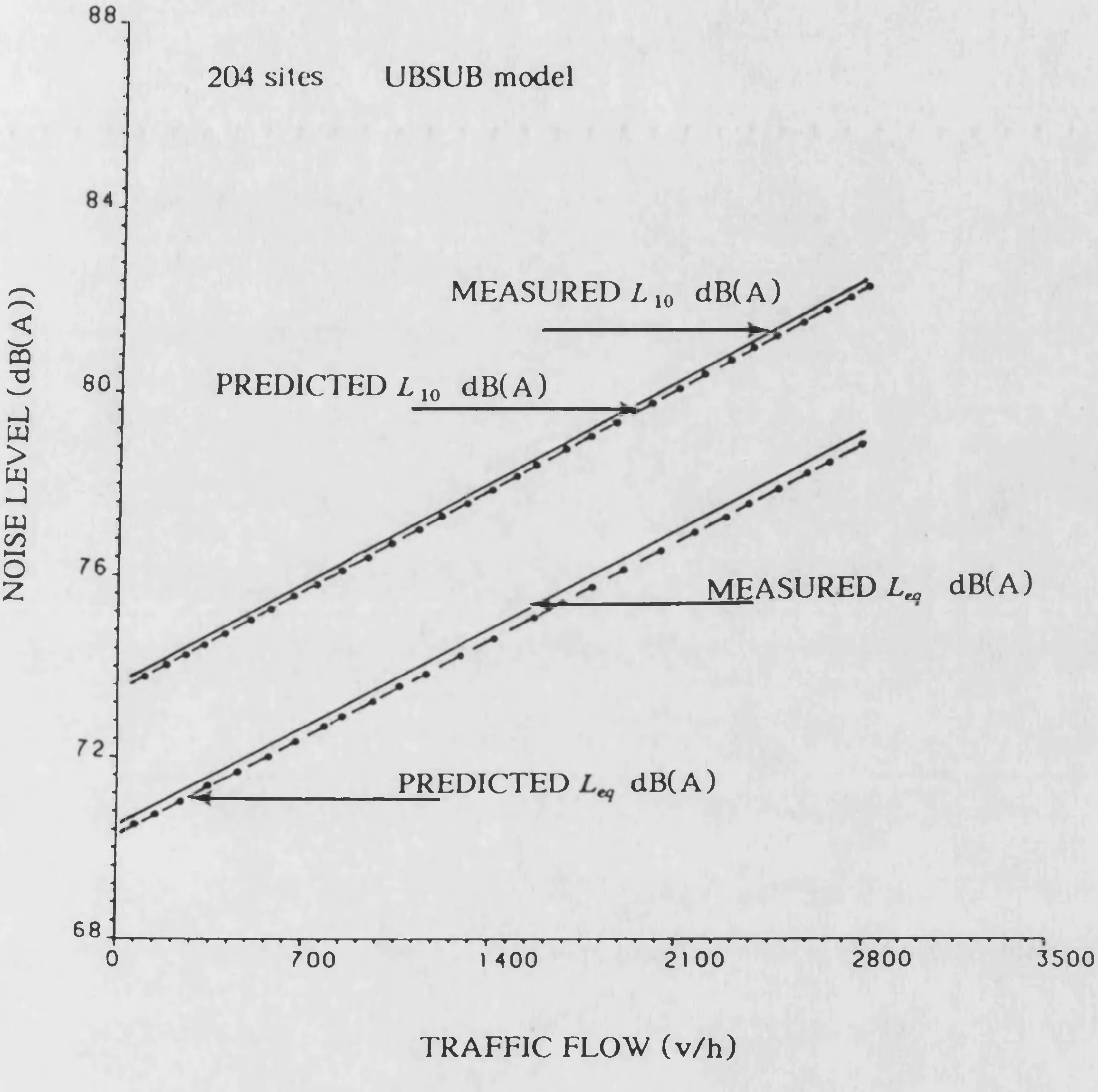


Fig 9.4 Comparison between measured noise level values and values predicted by the computer model for suburban & urban conditions

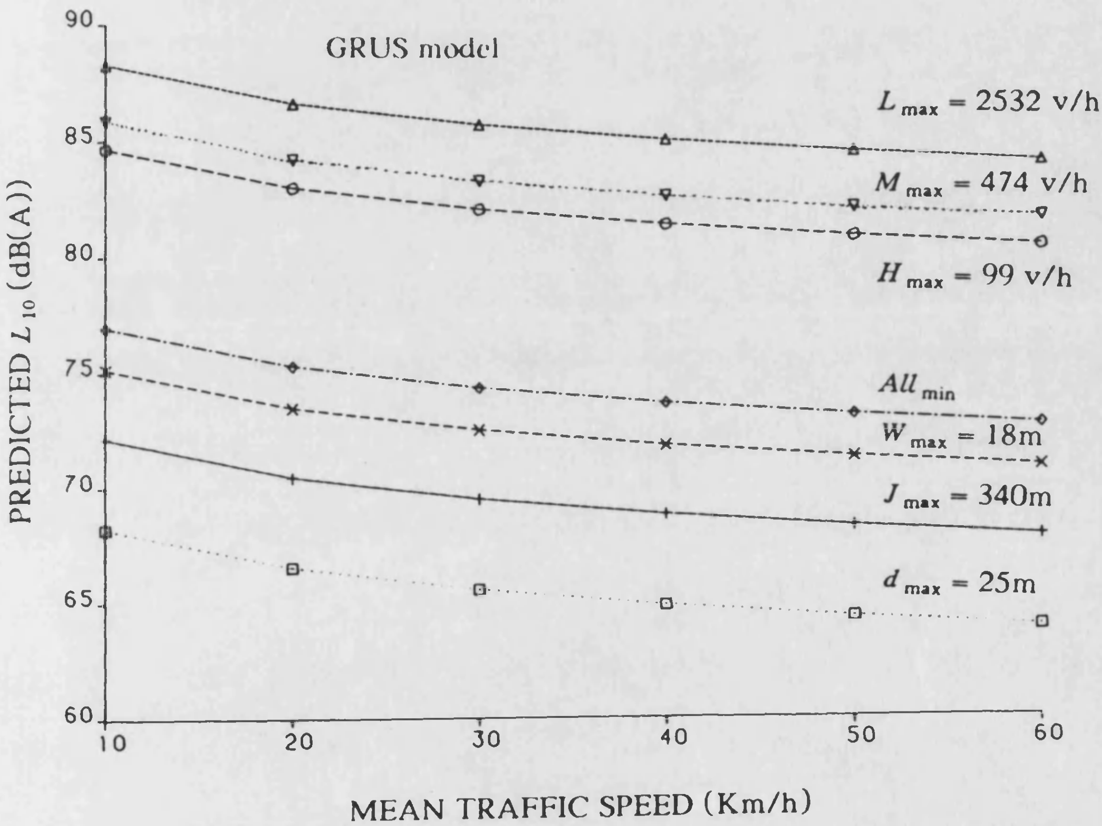


Fig 9.5 Predicted L_{10} versus traffic speed associated with various urban conditions

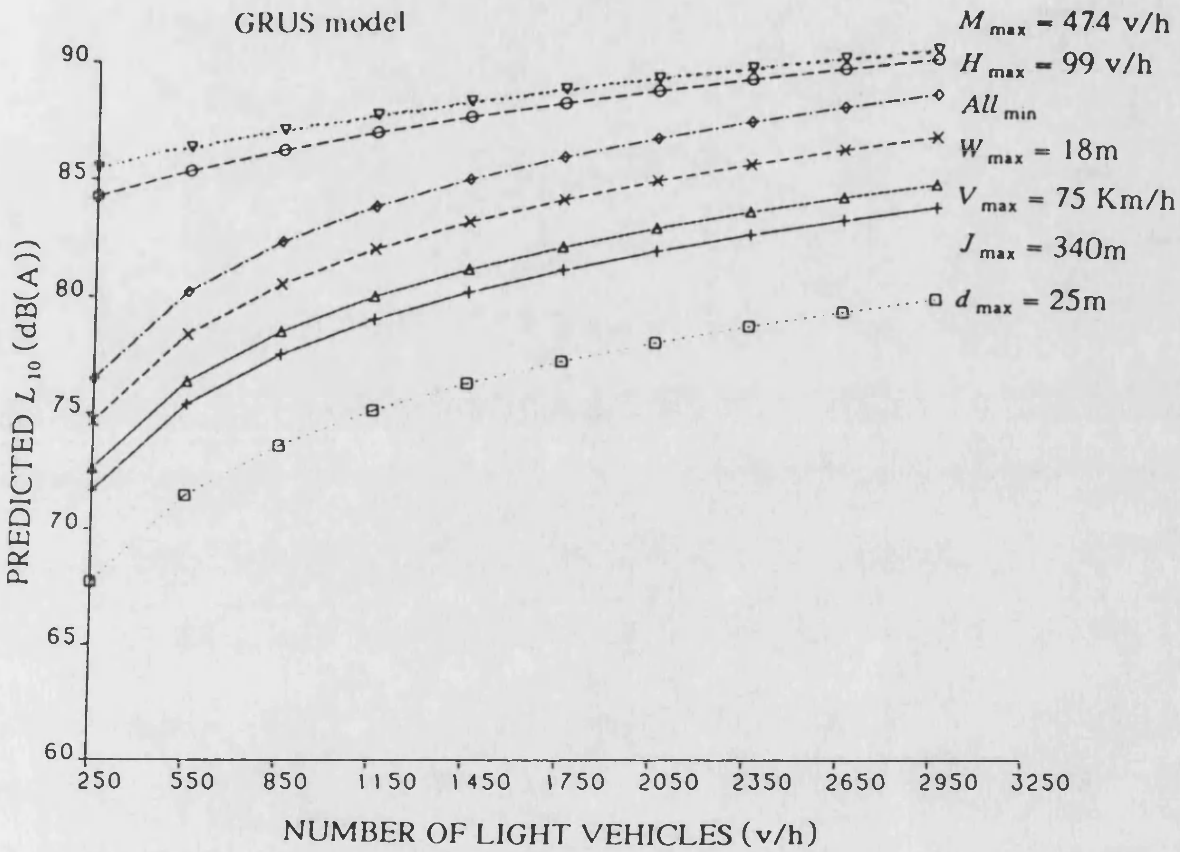


Fig 9.6 Predicted L_{10} versus number of light vehicles associated with various urban conditions

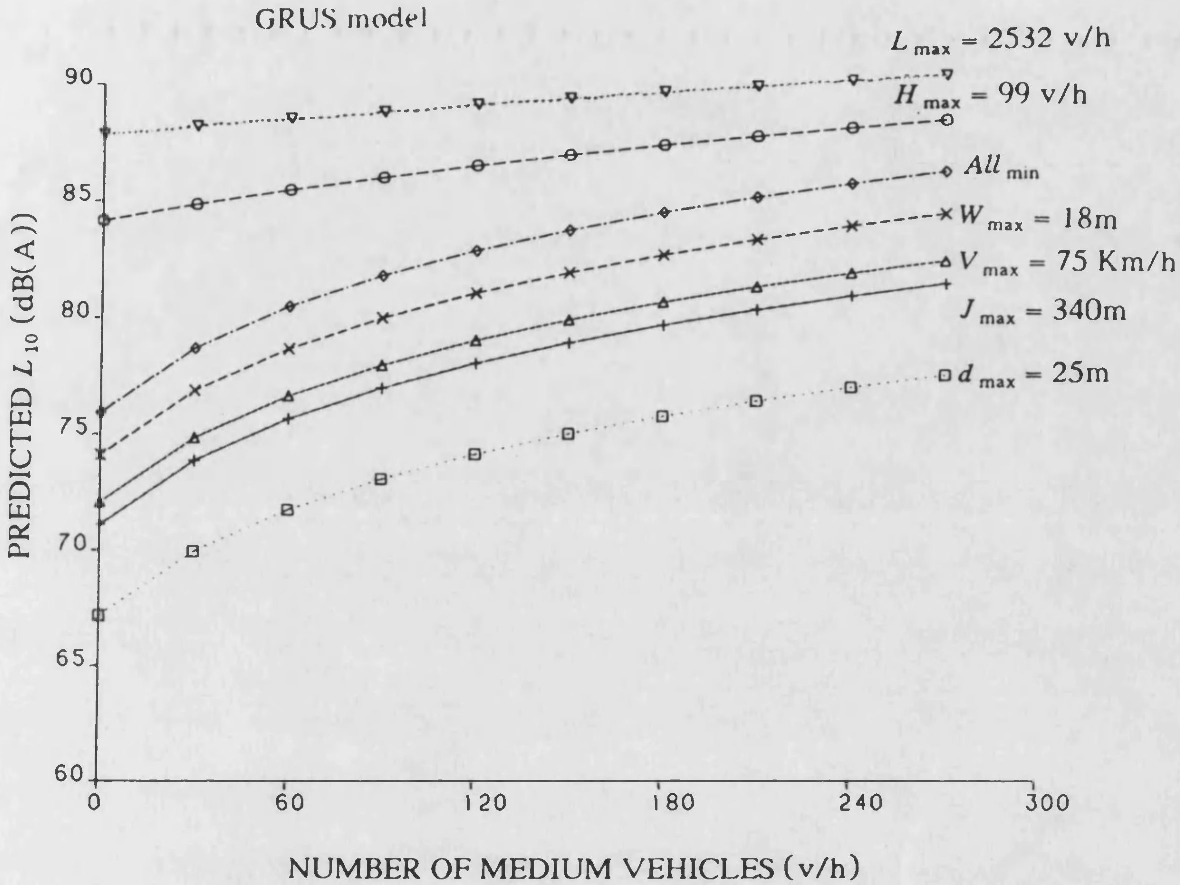


Fig 9.7 Predicted L_{10} versus number of medium vehicles associated with various urban conditions

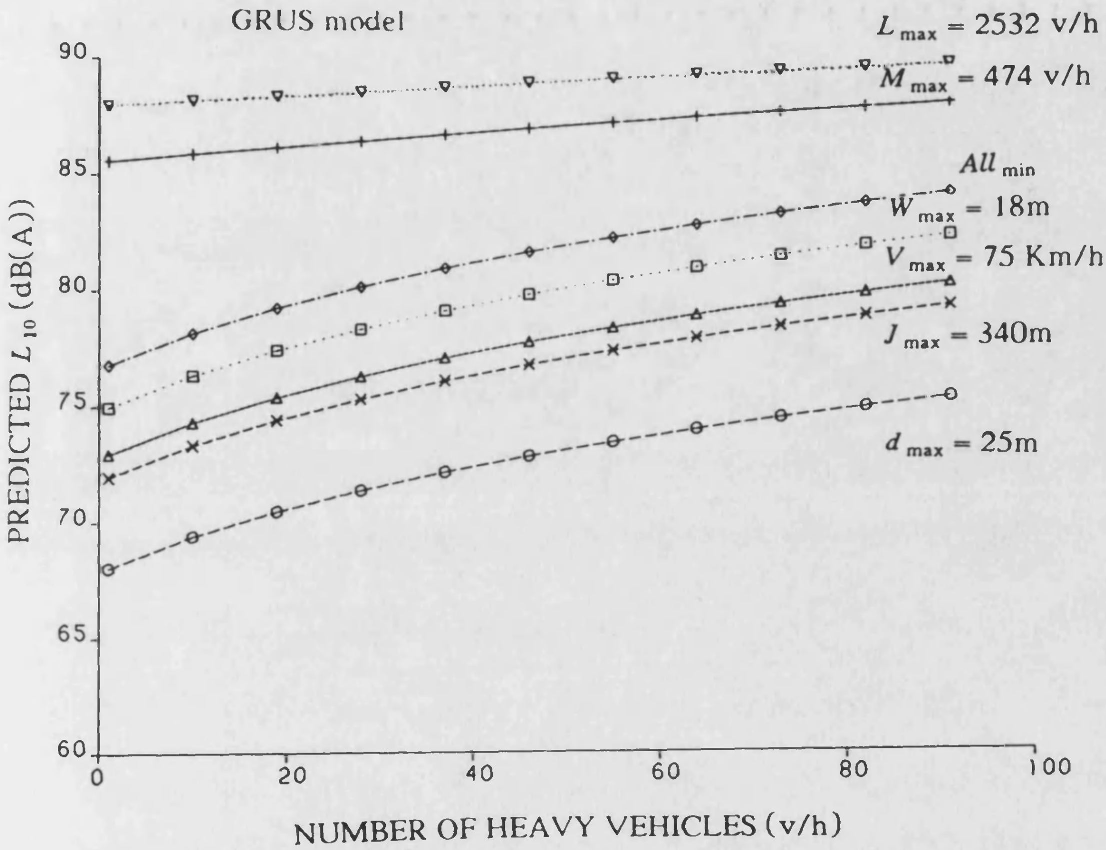


Fig 9.8 Predicted L_{10} versus number of heavy vehicles associated with various urban conditions

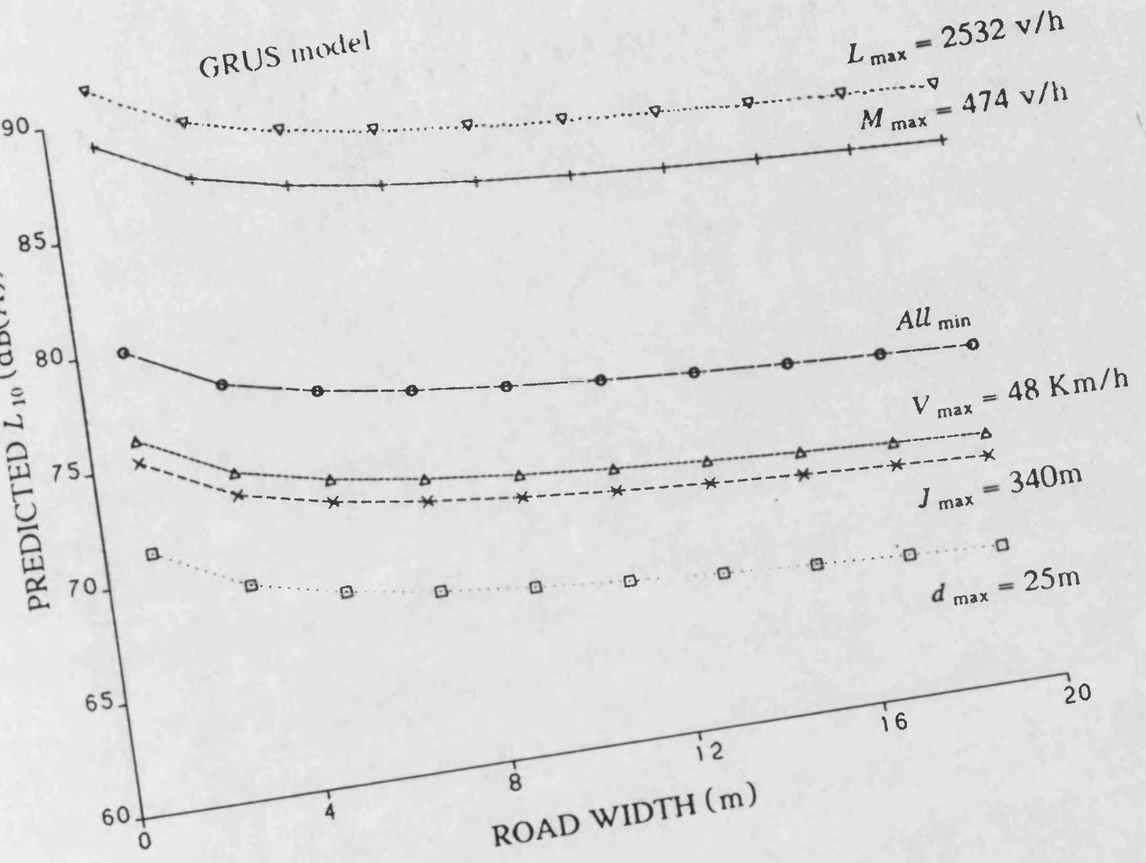


Fig 9.9 Predicted L_{10} versus road width associated with various urban conditions

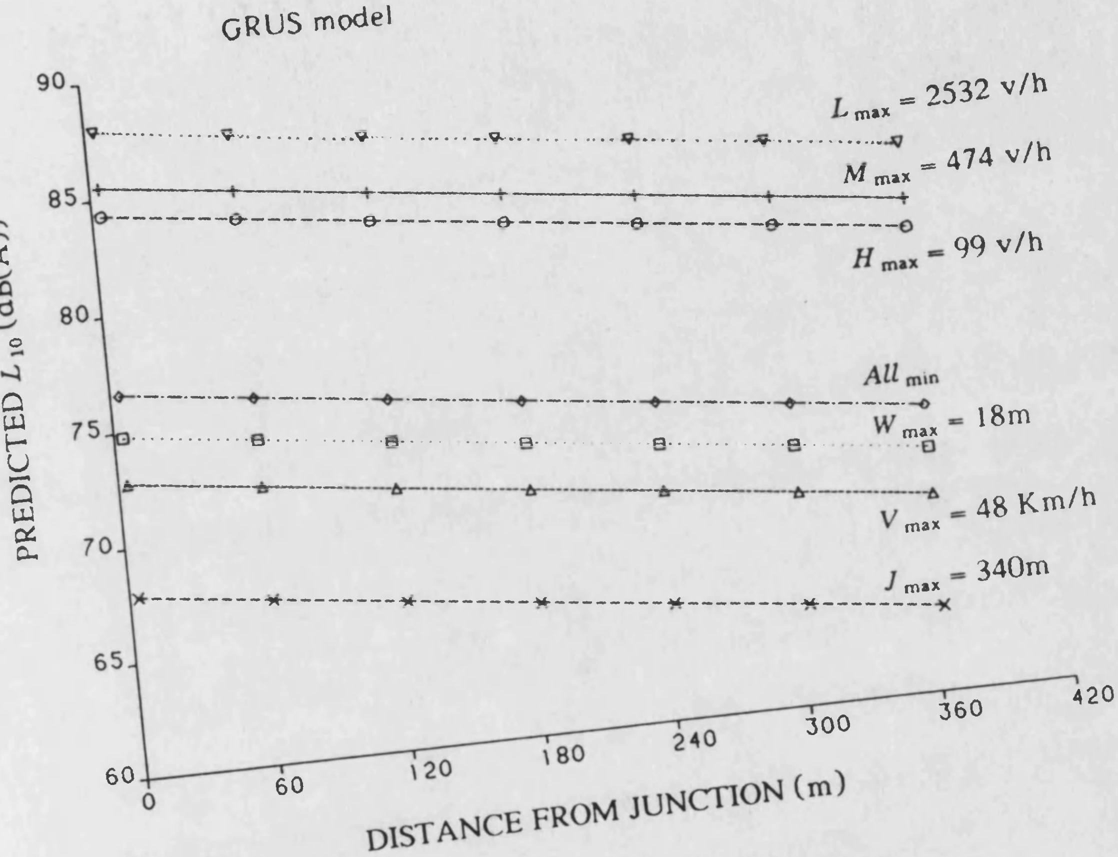


Fig 9.10 Predicted L_{10} versus distance from junctions associated with various urban conditions

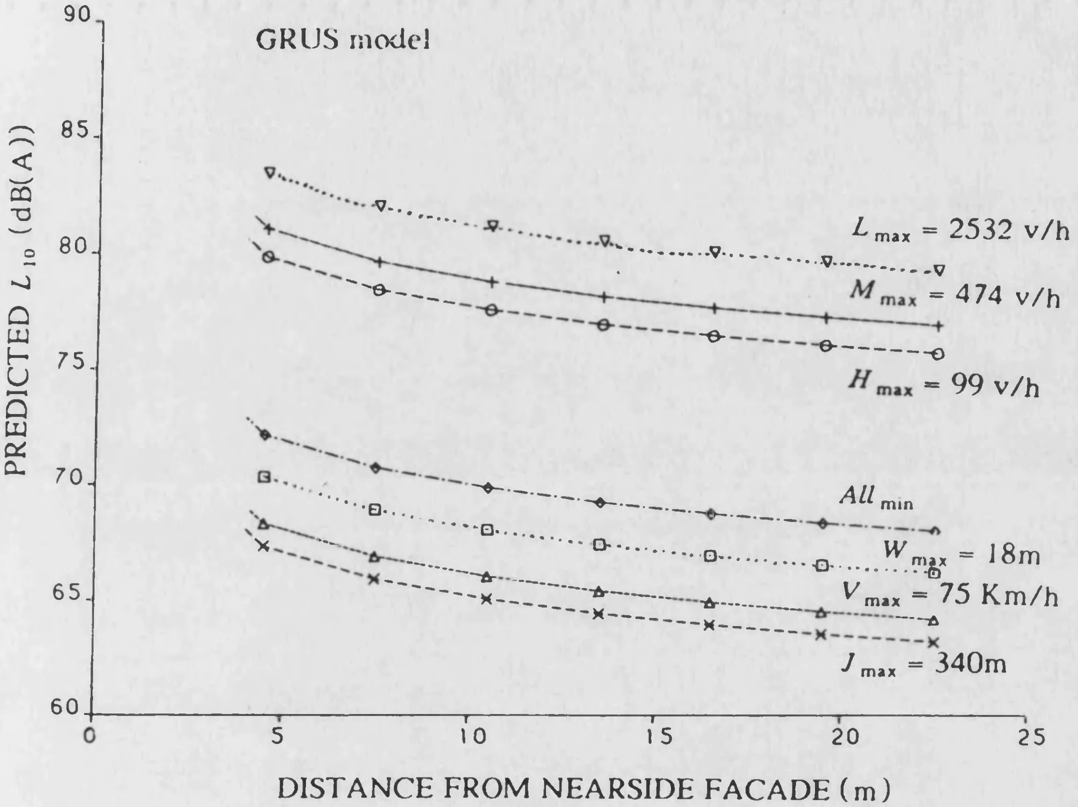


Fig 9.11 Predicted L_{10} versus distance between nearside building facade & nearside kerb associated with various urban conditions

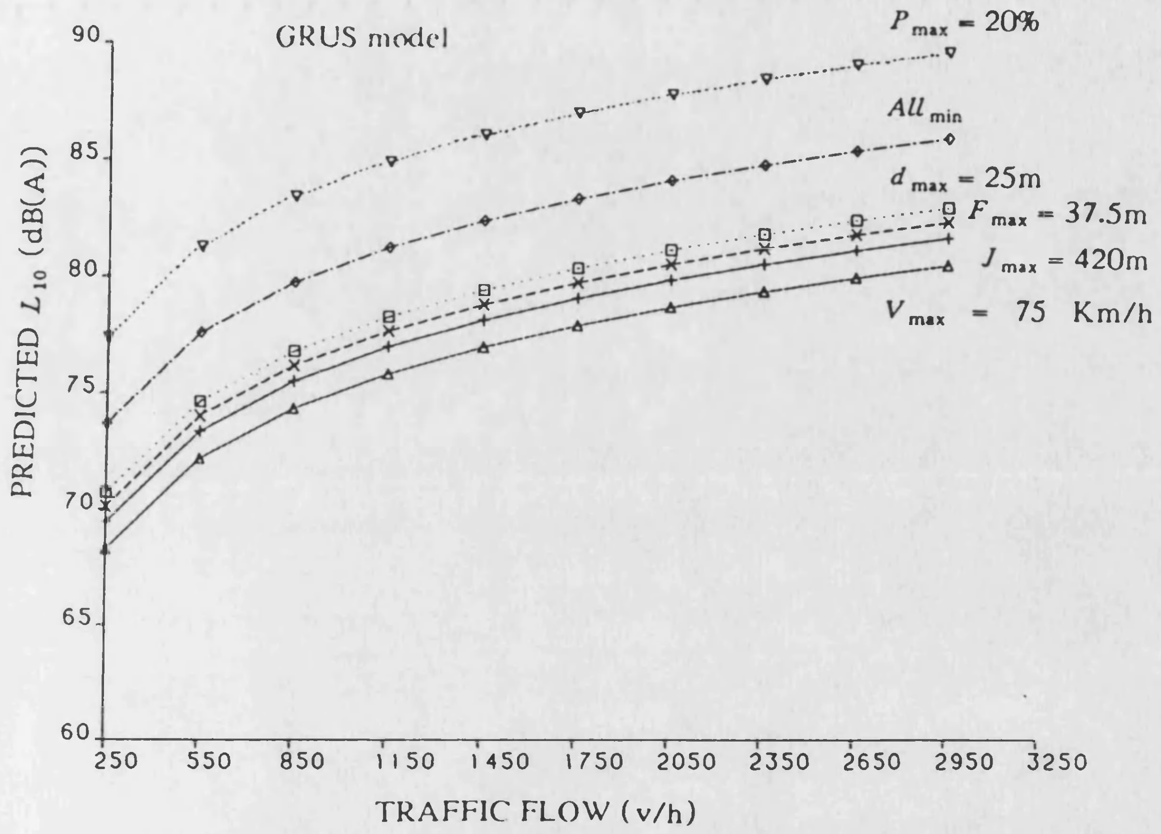


Fig 9.12 Predicted L_{10} versus traffic flow associated with various suburban & urban conditions

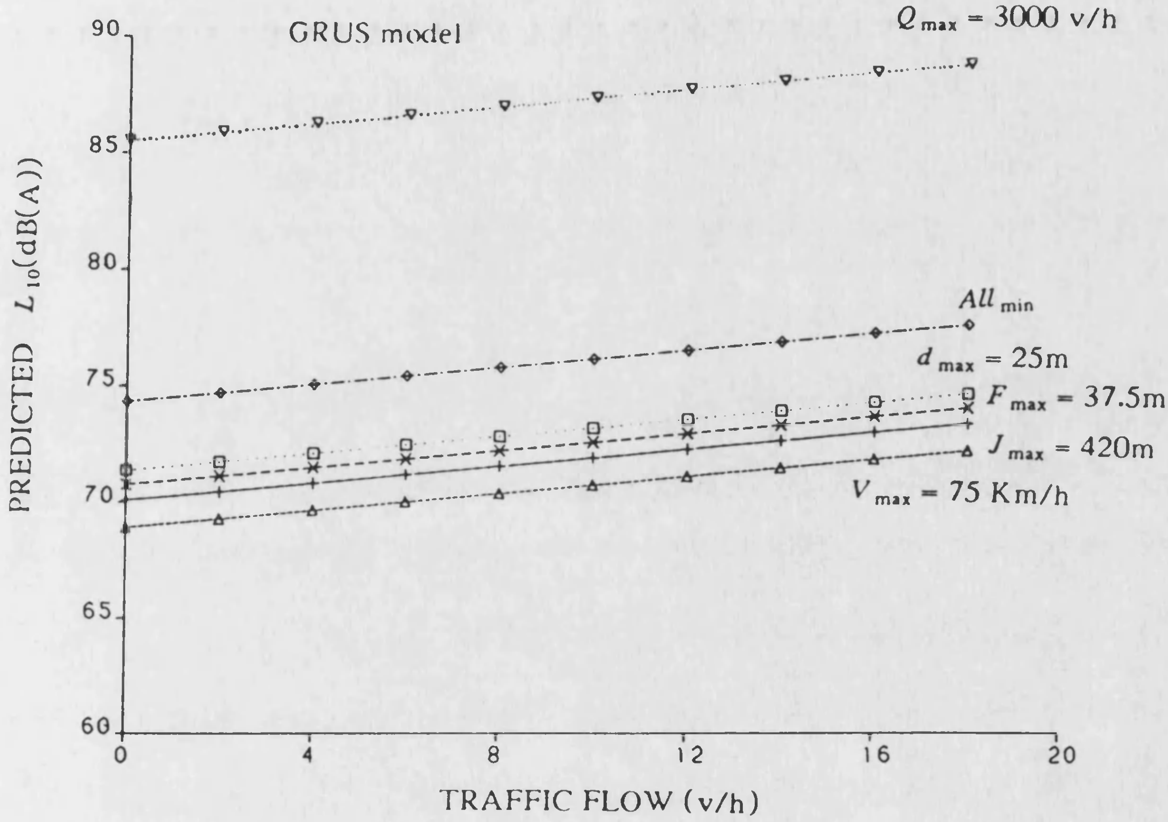


Fig 9.13 Predicted L_{10} versus percentage of medium & heavy vehicles associated with various suburban & urban conditions

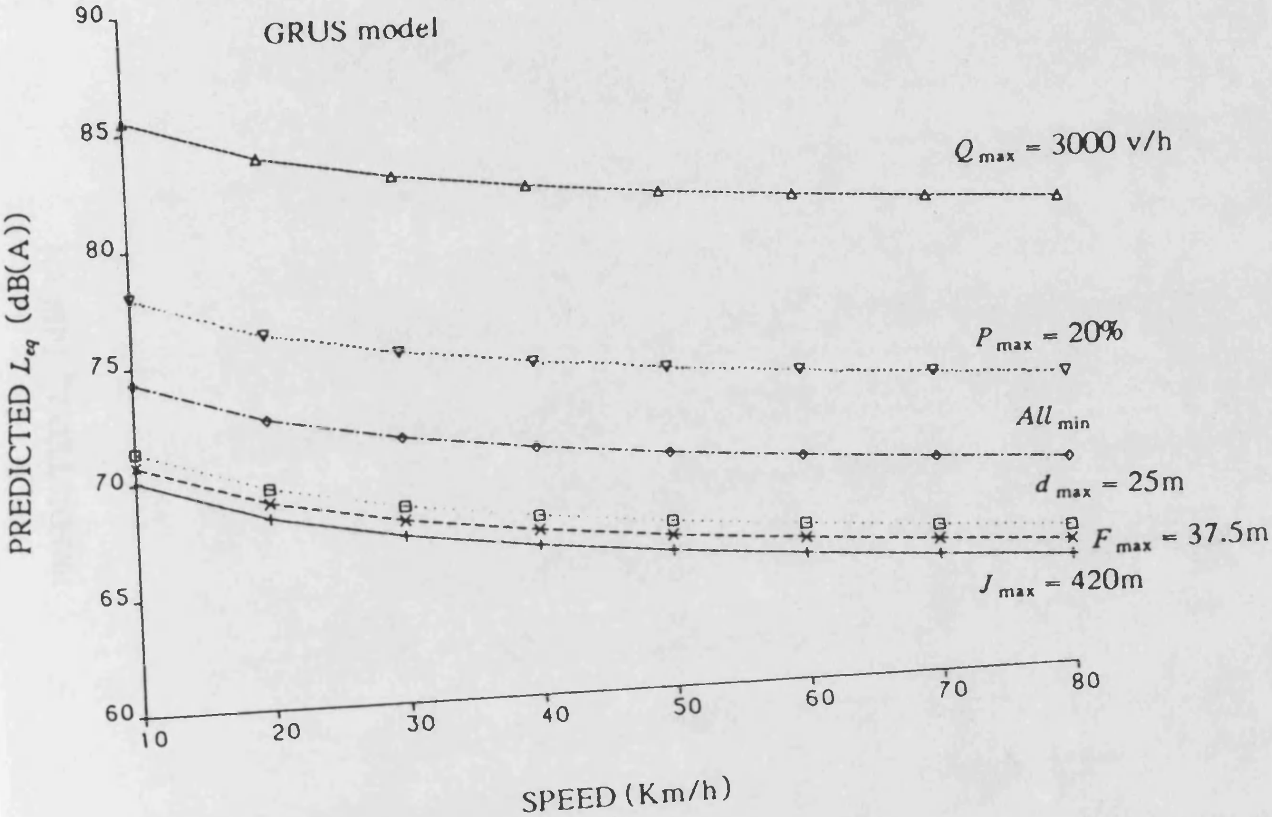


Fig 9.14 Predicted L_{eq} versus traffic speed associated with various suburban & urban conditions

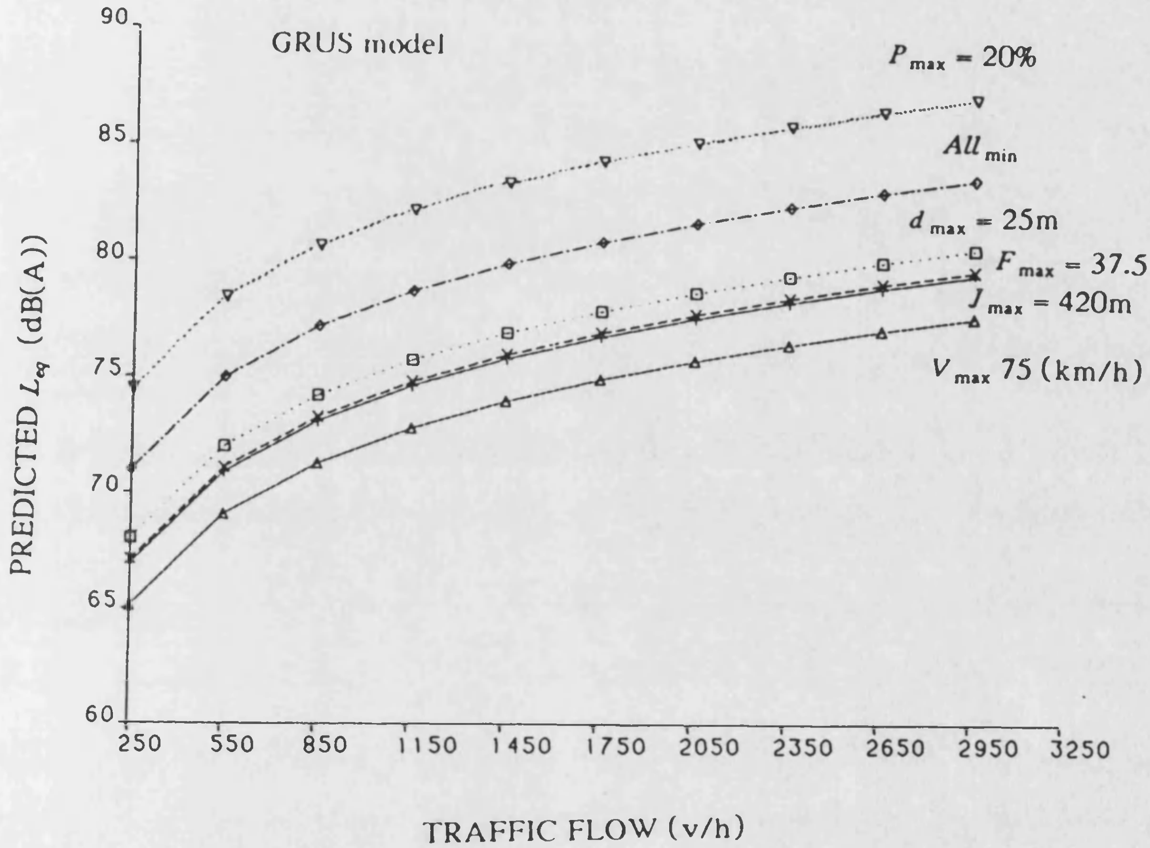


Fig 9.15 Predicted L_{eq} versus traffic flow associated with various suburban & urban conditions

CHAPTER TEN

GENERAL CONCLUSIONS

Road and building designers and planners can no longer carry out their work according to economic and traditional geometric elements alone. They must also consider such environmental factors as traffic noise exposure and annoyance. It is necessary to estimate the extent of the noise problem according to people's judgements, and also to develop standards for planning and design objectives, as knowledge in the field of traffic noise in built-up areas is incomplete. Some of the gaps may be filled by studying the causes of traffic noise and the attitude of people towards it.

The goal of the work undertaken in this thesis was to help advance current knowledge pertinent to the prediction and assessment of noise exposure and noise annoyance in urban and suburban contexts associated with non-free flowing traffic. This was accomplished through the development and validation of prediction procedures.

Since no reliable prediction method in this field was available, the research programme involved the consideration of the following main subjects: evaluation of the level of progress that has been achieved and to what degree it could assist in the development of this study; examination of the physical characteristics relating to noise generation; development of overall noise prediction models for urban and suburban conditions; investigation of people's reactions to traffic noise and its contributing factors and establishment of traffic noise annoyance prediction models; and development of comprehensive computer models. The practical means of attenuation of noise in built-up areas were also identified.

The newly developed prediction models were based on a wide-ranging programme of field surveys. These surveys covered 3528 thirty-minute noise-level measurements, at 266 sites, including 23 signalised intersections, 6 roundabouts and 15 priority junctions. The sites also covered 6 categories of landuse, 3 types of traffic conditions, and 40 dependent and independent variables. In addition, the answers given by a sample of 319 people to a questionnaire were included. The established models proved intrinsically more reliable than previous practice. They rely on components that were deliberately selected to facilitate the eventual use of them for design and land use planning purposes.

In addition to the conclusion presented at the end of each relevant section and chapter, general conclusions of some of the most significant findings are restated below.

Road transport has always been, and continues to be, a vital ingredient of the progress of civilisation. It is the most convenient method for the satisfactory movement of people and goods. The advantage which distinguishes road transport from other modes is its ability to provide so called 'door-to-door service'. During the last few decades, the accelerating spread of road vehicle use and ownership, together with population growth and the attraction of people into urban and suburban regions has resulted in modern societies in which noise emitted by road traffic seems to be an inevitable problem. So it could be inferred that the future of road transport is assured in spite of the resulting deterioration of the environment. Great efforts, therefore, must be made in order to estimate how the best use of motor vehicles can be achieved and how the traffic noise problem can be overcome, through the processes of landuse planning, design and the choice of construction components. It is from this basic standpoint that the research of this thesis has been carried out.

There are 3 main approaches to traffic noise abatement. These are related to the source of traffic noise, its transmission path and the receiver. Reduction of motor vehicle noise (at the noise source) is not an easy task and the hope of wide use of quiet vehicles is still a projection for the next decade. The alternative, therefore, is to work during the design and planning procedures on noise-reducing features, through the receivers and the path of propagation to them, to control noise exposure and annoyance. This has resulted in great demand for a reliable prediction method to serve as a measure to protect the surrounding community from the impact of traffic on the environment. The prediction method is also important for environmental legislation and evaluating strategies for the features of different road schemes. The availability of a prediction method can save time, money and it is convenient to have a prediction tool which relies on existing transportation engineering standards.

The importance of traffic noise in built-up areas where the flow of traffic is non-free has not been accompanied by a reliable prediction method to assess its influence. Studying the performance of such traffic noise levels has always been complicated due to the interaction between a large number of related variables. Previous studies gave little information as to how most of the related variables affect the level of noise when they act as individuals or in combination and previous prediction methods in this field have shown several limitations. This is because the methods were based on limited conditions and elements and inadequate for practical situations. The success of any prediction model depends on dealing comprehensively with the related variables of built-up contexts.

One of the earlier stages of this work concentrated on determining which variables were to be included. The significance of 40 variables was eventually considered to avoid the limitations encountered in previous studies. They covered the majority of noise-contributing factors and there was a need to investigate them. The period of hourly sampling was also identified as lasting 30 minutes, as this was found to give more accurate results than, for example, the common practice of 5-15 minutes.

Studying the variables of interest in combination was found to represent the real situation more effectively than considering them individually or in pairs. Individual examination of the variable was difficult because of the complex interaction between them. The coefficient of correlations was increased significantly when the combined variables were used. The investigation into the traffic noise characteristics of the 3 common types of road junctions resulted in the establishment of new accurate models for prediction of noise level in the vicinity of traffic light intersections, roundabouts and priority junctions. The models gave a high level of accuracy when they related L_{10} to traffic speed, road width, distance from considered junction, traffic composition and distance from nearside building facade. The models were a clear indication that the situation can be modelled although little has been produced in this field.

Two kinds of overall prediction models were developed, based on the comprehensive data gathered on various noise characteristics in urban and suburban areas between 7.00 and 19.00 hours.

(1) It was concluded that for urban conditions (48 km/h) L_{10} was best determined as a function of mean traffic speed and composition (3 classes of vehicles); and the distance of surrounding building facades and various road junctions. The findings relied on field measurements taken at 172 urban positions where there were signalised intersections (95 sites), roundabouts (49 sites) or priority junctions (28 sites).

(2) For urban and suburban conditions, where the speed ranged between 10-75 km/h at 204 positions, it was found that L_{10} was best predicted as a function of traffic flow and speed; percentage of medium and heavy

vehicles; and distance from surrounding facades and from various types of junctions.

A prediction models were also developed using L_{eq}, despite the lack of information in this area. L_{eq} was found to follow the same performance under both the above mentioned situations in spite of showing a slightly lower level of correlation. In addition, models using L_{50} and L_{90} were developed.

The differences between the above models lay in their component variables. Under urban conditions, traffic composition was found to contribute to a high level of noise. It was also found to be important to consider three classes of vehicles rather than two classes as is common. The levels of noise always increased when traffic composition changed to include more heavy and medium vehicles.

Obvious relationships also emerged between the adjacent buildings and level of traffic noise. The relation between noise levels and nearside facade was mainly dependent on distance between facade and nearside kerb. The relation of noise with farside facade was subject to the distance between measurement point and nearside kerb, road width and distance between farside kerb and farside facade. Noise level was found to decrease with increasing facade distance.

Clear interaction between the level of noise and distance from various types of junctions was obtained. The level of noise decreased with the increasing distance from junctions, depending on related factors such as type of junction and speed.

Speed of traffic followed the same pattern, as noise level decreased with increasing speed, depending on road length and frequency of junction, unlike the common practice when calculating L_{10} from freely flowing traffic.

The models representing urban and suburban conditions indicated that traffic flow and percentage of medium and heavy vehicles were the best predictors, unlike the above urban models where composition of traffic played a significant role. High speed, length of the road and greater distance between junctions were found to be the main reasons. The vehicles at high speed (over 48 km/h) required fewer gear changes and less maneuvering. So the difference in the noise level generated from various vehicles decreased. Noise levels always increased with increase in traffic flow and percentage of medium and heavy vehicles and decreased with increases in speed, distance of farside and nearside facade and distance from junctions.

The overall prediction models were practical, accurate and reliable.

Attempts to control traffic noise in built-up environments have been hampered by insufficient knowledge of the complex interaction between traffic noise level and various negative human responses to this noise and its causes. This thesis therefore included an investigation of the attitude of people towards environmental noise in the urban area of Bath. The Social Survey was performed by means of an appropriate questionnaire (73 items) which was applied to a sample of the population. Examination of the answers to the questionnaire involved two stages of analysis. The first dealt with the characteristics of the study sample. The result indicated that traffic noise seems to be a major environmental problem. The answers clearly confirmed the importance of the considered variables of this study (e.g. existence of junctions) as factors contributing to traffic noise annoyance in built-up situations. The second stage also confirmed L_{10} and L_{eq} as the best predictors, as well as confirming the contributing variables. In addition, this stage dealt with the development of new prediction models which relate the (created scale) Overall Traffic Noise Annoyance Index (OTNAI) to noise exposure indices L_{10}, L_{eq} and L_{50}. The OTNAI was established as the average value of 19 response scores (on a 5-point scale) given in answer to the questionnaire. It represents the essential factors of noise annoyance such as firstly, noise sources, secondly, level of propagated noise and thirdly, interference with people's normal activities. OTNAI showed its reliability and gave a high level of correlation such as R=0.84 with L_{10}.

In spite of the accuracy and reliability of the developed prediction models which were discussed earlier for urban and suburban conditions, there are still unanswered questions, since the factors affecting traffic noise characteristics in interrupted flow are numerous. Despite the consideration of the 'basic variables' by the above models, there is still a need for other variables to be employed. The 'descriptive variables' are representative of these factors (e.g. residential area). These descriptive variables cannot be covered by mathematical methods as the other variables are, although they are necessary at some planning and design stages which need detailed information. Therefore, the interrelation of traffic noise characteristics in built-up situations demanded the establishment of a new comprehensive prediction tool such as the computer model (UBSUB). This kind of model was ideally suited to gather a large number of relevant variables and conditions. Another reason behind the introduction of the model was that it is practical to have a tool capable of assessing the specifications of the independent variables and various indices of noise exposure and annoyance at the same time. UBSUB was established to predict noise levels L_{10}, L_{50}, L_{90} and L_{eq} dB(A) associated with traffic flow and speed, vehicle types, traffic characteristics, road layout, type of junctions, location of buildings, landuse and weather conditions. The model was also designed to predict traffic noise annoyance (OTNAI) in terms of L_{10}, L_{eq} & L_{50}. UBSUB utilises the empirical formulas which were developed during the course of the study and is based on a wide-ranging of field investigation, under urban and suburban conditions. It estimates up to 2000 sites at each run, but the user may change this if a larger number is required. The model covers almost all the variables which characterise the structure of built-up environments and are necessary for a comprehensive environmental policy. UBSUB also has the advantage of a great deal of flexibility and is based on a common computer language.

A graphic computer model (GRUS) to estimate the effects of individual variables on noise level has also been developed. The model is capable of modifying the variable individually to maintain the recommended environmental policy. It examines 170 probabilities at each run associated with 27 figures. GRUS can further aid the decision makers in this task by comparing various results, and providing visual representation.

The prediction models of this thesis were thorough because they covered noise annoyance and all the noise exposure indices commonly used, despite the lack of knowledge in this field. The traffic noise models showed a high level of accuracy probably because they are based on all the common characteristics of urban and suburban environments. The consideration of the related variables (e.g. speed) which were ignored by previous practice increased the performance of the models significantly. There is probably another reason for the good performance of the models, which is that the measurements of noise and contributing variables were made along the accelerating and decelerating streams of traffic, associated with different kinds of junctions and various buildings on both sides. The measurements also covered all the typical categories of built-up land use and traffic. Such measurements without doubt meant that the output of the models closely represented the real situation. The period of sampling (i.e 30 minutes per hour), number of daily measurements (i.e 12) and the larger number of considered sites (e.g. 204) are probably other reasons why these models represent the actual problem. In addition, the social survey further confirmed the significance of the models. It identified the built-up features which cause a high level of annoyance, and these features have already been employed by the models. The annoyance models also proved appropriate, as they were based on all elements of annoyance associated with reliable traffic noise measurements.

Neither limiting traffic nor increasing the distance between buildings and the road network are easy targets in built-up situations. Application of the developed noise exposure and noise annoyance models has shown that a traffic noise abatement policy, through design and planning operations, would be the most convenient protection against noise disturbance. This would include consideration of traffic noise in the processes of transportation planning, road building, traffic management, urban planning and building construction. Meanwhile noise problems cannot be minimised solely by the control of noisy vehicles, which is the target of current research in many countries.

In terms of their practical application the developed prediction models may be classified into two categories. Firstly, the 'simplified models' which can be employed for rapid prediction or everyday requirements. These include the aforementioned models for urban and suburban conditions as well as annoyance models. The models can be employed when evaluation is required in terms of the 'basic variables' only. An example of this is the primary evaluation of a building location in terms of traffic composition and distance from the road. Secondly, the 'detailed models' which can be used for detailed environmental schemes. These include the computer model (UBSUB) and the graphic computer model (GRUS). UBSUB can be employed when evaluation is required in terms of 'basic and descriptive variables', for example in the appraisal of detailed urban area plans or a comprehensive traffic management scheme. The GRUS can be used to maintain the running of the recommended system. The choice of using a 'simplified model' or a 'detailed' one depends on the purpose of the investigation.

Finally, the models presented by this research are more reliable than those developed previously. They rely on a variety of conditions, consider all the common relevant variables and are able to satisfy the various requirements of environmental engineers and others concerned with the assessment of traffic noise and reaction of people. It is hoped that this attempt can contribute for closing the gap that exists in information available for the appraisal of noise levels emitted from restricted traffic flow in urban and suburban areas.

A further development of this work might be in the validation of the models against other field measurements. Examination of the effect of the individual variables on noise level would be beneficial, especially the effect of speed of traffic, the various junctions and building facades. More field data are required to test the relationship between noise level and elevation of buildings. More investigation of people response to noise and its causes would also be useful.

Some of the work reported in this thesis has been published in journals and at conferences. The nine relevant publications are listed in Appendix D.

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APPENDIX A

DATA FORMS

University of Bath
School of Architecture & Building Engineering
Traffic Noise Survey

Form 1A-NFFT
Serial no:
Date:

Site:____

Position no:______________________ Run no:__________________________

Time commenced:___________________ Time ended:______________________

Traffic conditions:____________________________________

Traffic directions:__________________________ Number of lanes:______________

Traffic characteristics alongside the lane:____________________

Noise source:______________________ Type of road surface:__________

Average speed of traffic:_______ Km/h Width of road:______________________

Distance from the kerb to receiver:____m. Height of receiver:_______m.

Distance from the receiver to the nearest node:____________________m.

Type of node:____

Distance from the kerb to nearside building facade:______________m.

Distance from the kerb to farside building facade:_______________m.

Predominant land use:________________________________

Parking, pedestrian crossing & bus stop status:__________________________

Weather conditions:____

Tape no:______________ Tape start no:______________ Tape finish no:_________

Run length:_________min. Photo no:_______________________

Sound level meter(dB):

Calibration signal:______________________________

Range setting for calibration:__________________

Range setting for traffic noise measurements:_______

General remarks:-

____

____

Data form 1A

University of Bath
School of Architecture & Building Engineering
Traffic Noise Survey
Traffic count

Form 2A - NFFT
Serial no:
Date:

Light Vehicles						Medium Vehicles						Heavy Vehicles			
Cars		Vans		Others		Vans		Lorries		Buses & Coaches		Vans		Lorries	
N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
v/h						v/h						v/h			

	Motor Cycles				Others	
	Light		Heavy			
	N	F	N	F	N	F
TOTAL						

Statistical analyser readings:

1________	2________	3________
4________	5________	6________
7________	8________	9________
10________	11________	12________

S.P.L. dB(A)	100	95	90	85	80	75	70	65	60	55	50	45	40
______sec. count													
% count													

Data form 2A

University of Bath

School of Architecture & Building Engineering

Traffic Noise Survey

Form: 3A-NFFT

Serial no:

Date:

Site:______________________________ Time:________________________________ hours

Position no:____________________ No. of runs:____

Traffic variables:

Mean traffic flow __________________________________v/h

Mean number of light vehicles _______________________v/h

Mean number of medium heavy vehicles ______________v/h

Mean number of heavy vehicles _____________________v/h

Mean number of motor cycles __________________________v/h

Mean speed _____________________________________ Km/h

Others ____

Noise levels - dB(A)

Mean L_{10} _____________________________________

Mean L_{50} _____________________________________

Mean L_{90} _____________________________________

Mean L_{eq} _____________________________________

Location map:

General remarks:

____

____

Data form 3A

APPENDIX B

TYPICAL OUTPUT OF NFNOS PROGRAM

(204 urban and suburban positions)

Typical output of NFNOS program
(204 positions - 6 predictors, L_{10} dB(A)

```
 -- regr L10 6 LgV,LgQ,P,LgF,J,LgN
the regression equation is
y =    58.6 -  5.99 x1 +  11.4 x2
   + 0.183 x3 -  5.94 x4 -0.0102 x5
   -  2.46 x6
```

	column	coefficient	st. dev. of coef.	t-ratio = coef/s.d.
	--	58.572	1.046	55.99
x1	LgV	-5.9943	0.4851	-12.36
x2	LgQ	11.4260	0.3009	37.98
x3	P	0.18302	0.01328	13.78
x4	LgF	-5.9366	0.8006	-7.41
x5	J	-0.010238	0.001057	-9.68
x6	LgN	-2.4575	0.2633	-9.33

```
the st. dev. of y about regression line is
s = 0.770
with ( 204- 7) = 197 degrees of freedom

r-squared = 93.8 percent
r-squared = 93.6 percent, adjusted for d.f.

analysis of variance
```

due to	df	ss	ms=ss/df
regression	6	1827.423	304.570
residual	197	121.015	0.614
total	203	1948.438	

further analysis of variance

ss explained by each variable when entered in the order given

due to	df	ss
regression	6	1827.423
LgV	1	245.655
LgQ	1	1082.375
P	1	76.959
LgF	1	321.334
J	1	47.595
LgN	1	53.504

durbin-watson statistic = 1.39

Site NO.	MEAS.L10 204	PRED.L10 204	RESIDUAL 204
1	83.7000	83.6245	0.07546
2	83.6000	83.5996	0.00039
3	84.5000	83.6231	0.87687
4	83.5000	82.8365	0.66348
5	83.0000	81.8874	1.11262
6	82.3000	82.2047	0.09528
7	79.4000	79.8532	-0.45317
8	83.2000	83.4139	-0.21387
9	80.5000	80.9201	-0.42012
10	80.6000	80.1428	0.45725
11	78.6000	79.3399	-0.73993
12	75.6000	76.4691	-0.86913
13	75.3000	76.0668	-0.76682
14	73.6000	73.7307	-0.13069
15	77.5000	76.3519	1.14813
16	74.9000	74.5444	0.35555
17	81.2000	81.6257	-0.42574
18	75.9000	75.8188	0.08119
19	74.4000	74.9883	-0.58832
20	75.5000	75.7364	-0.23635
21	74.6000	74.6041	-0.00411

22	74.6000	73.8787	0.72126
23	80.8000	78.6446	2.15540
24	79.7000	78.0067	1.69327
25	83.6000	83.5070	0.09298
26	83.3000	83.5354	-0.23536
27	83.6000	81.9871	1.61285
28	83.3000	81.9862	1.31383
29	80.4000	79.6465	0.75346
30	84.8000	84.9034	-0.10343
31	84.0000	83.1827	0.81734
32	80.5000	80.5414	-0.04138
33	78.4000	78.7131	-0.31310
34	77.1000	75.3789	1.72105
35	81.1000	81.2998	-0.19977
36	80.9000	80.1612	0.73879
37	78.7000	79.2080	-0.50804
38	78.0000	78.4868	-0.48676
39	79.5000	80.9338	-1.43375
40	76.2000	76.0003	0.19970
41	80.4000	79.8253	0.57469
42	76.3000	76.1393	0.16067
43	75.7000	75.6748	0.02523
44	74.0000	74.5008	-0.50084
45	80.7000	80.2575	0.44250
46	78.3000	78.9275	-0.62754
47	75.9000	76.4946	-0.59457
48	74.2000	75.2170	-1.01698
49	77.7000	78.4887	-0.78874
50	79.1000	78.5263	0.57365
51	81.6000	80.0793	1.52072
52	79.2000	79.6849	-0.48490
53	76.3000	76.0268	0.27321
54	75.3000	75.5345	-0.23448
55	75.7000	76.0398	-0.33985
56	80.7000	80.5757	0.12434
57	79.7000	80.2909	-0.59090
58	79.0000	78.3517	0.64834

59	80.4000	80.8728	-0.47280
60	75.2000	75.9981	-0.79812
61	82.2000	82.0624	0.13757
62	80.3000	79.3199	0.98007
63	81.0000	79.9169	1.08314
64	80.0000	78.9116	1.08837
65	78.1000	77.1975	0.90251
66	77.9000	77.1136	0.78643
67	79.1000	79.5017	-0.40174
68	80.6000	79.5854	1.01465
69	79.3000	79.3348	-0.03477
70	73.0000	71.7038	1.29620
71	73.6000	72.6971	0.90294
72	80.3000	79.8054	0.49462
73	80.1000	79.3149	0.78510
74	77.1000	76.8824	0.21755
75	81.4000	80.9750	0.42503
76	79.1000	79.5992	-0.49916
77	78.9000	78.5683	0.33168
78	78.7000	77.9631	0.73691
79	77.3000	76.0194	1.28061
80	75.4000	75.8908	-0.49082
81	76.0000	75.6983	0.30169
82	75.9000	76.8193	-0.91927
83	75.1000	75.5913	-0.49129
84	77.7000	77.4133	0.28673
85	76.1000	75.2522	0.84780
86	77.8000	77.2173	0.58271
87	75.7200	74.7593	0.96068
88	79.1000	79.5130	-0.41304
89	78.6000	78.2135	0.38653
90	77.2000	77.8220	-0.62197
91	75.9000	76.9323	-1.03231
92	75.7000	76.3074	-0.60739
93	76.0000	76.5552	-0.55521
94	76.7000	77.3203	-0.62033
95	75.3000	76.0526	-0.75258

96	73.0000	73.9621	-0.96214
97	75.2500	76.3432	-1.09319
98	77.6000	77.4396	0.16040
99	75.4000	76.6086	-1.20865
100	77.8000	77.8269	-0.02685
101	77.1000	77.3946	-0.29455
102	79.5000	78.4634	1.03664
103	76.7000	76.6876	0.01244
104	70.6000	70.6129	-0.01285
105	70.6000	71.2002	-0.60023
106	74.3000	74.4165	-0.11648
107	73.2000	73.4918	-0.29185
108	79.6000	78.3314	1.26858
109	73.3000	73.1501	0.14991
110	72.5000	71.4259	1.07410
111	69.6000	70.2718	-0.67183
112	76.1000	75.8759	0.22406
113	76.3000	76.4098	-0.10982
114	77.7000	77.1905	0.50946
115	75.9000	75.6478	0.25224
116	81.9000	80.4573	1.44268
117	79.6000	78.1277	1.47227
118	76.0000	74.9603	1.03967
119	78.8000	78.3689	0.43105
120	76.3000	75.9647	0.33532
121	69.8000	70.1535	-0.35348
122	80.5000	79.8997	0.60028
123	80.4000	79.4231	0.97687
124	77.2000	76.5700	0.63000
125	77.3000	76.6750	0.62495
126	74.4000	74.1011	0.29895
127	78.7000	77.1150	1.58501
128	77.8000	77.3885	0.41147
129	76.9000	76.2410	0.65905
130	78.0000	78.3622	-0.36218
131	76.0000	75.5094	0.49056
132	78.4000	78.9358	-0.53577

133	76.6000	76.7557	-0.15572
134	75.0000	75.3288	-0.32880
135	80.4000	80.5079	-0.10791
136	82.2000	82.6930	-0.49297
137	79.5000	79.9821	-0.48213
138	78.6000	78.0996	0.50040
139	76.4000	76.5971	-0.19708
140	76.1000	75.5901	0.50988
141	75.4000	75.7976	-0.39760
142	76.4000	77.7007	-1.30071
143	81.2000	80.6930	0.50704
144	78.5000	78.1137	0.38627
145	77.9000	77.7374	0.16261
146	81.0000	79.5502	1.44980
147	76.2000	76.6260	-0.42602
148	75.7000	75.0618	0.63816
149	74.7000	75.1598	-0.45982
150	74.7000	74.9547	-0.25466
151	74.8000	74.9105	-0.11052
152	74.7000	75.6844	-0.98438
153	75.9000	77.1811	-1.28112
154	75.8000	75.5707	0.22933
155	74.5000	73.7368	0.76324
156	70.3000	70.5778	-0.27780
157	77.6500	77.4438	0.20618
158	75.2000	74.8651	0.33491
159	77.3000	76.1898	1.11025
160	76.2000	76.1419	0.05810
161	76.9000	75.7985	1.10151
162	69.3000	70.5694	-1.26936
163	72.3000	72.8729	-0.57286
164	73.0000	73.6385	-0.63854
165	74.0000	74.4444	-0.44444
166	73.8000	74.9524	-1.15236
167	82.3000	80.7099	1.59013
168	76.2000	76.6074	-0.40745
169	77.3000	78.1749	-0.87490

170	76.2000	75.9071	0.29289
171	75.8000	75.4357	0.36431
172	72.2000	71.4525	0.74750
173	79.4000	80.2247	-0.82471
174	78.8000	78.8072	-0.00717
175	78.0000	78.7040	-0.70403
176	77.5000	77.3231	0.17687
177	81.5000	82.3474	-0.84738
178	79.8000	80.6915	-0.89151
179	77.7000	78.2977	-0.59767
180	82.0000	83.2909	-1.29090
181	79.7000	80.1767	-0.47672
182	78.3000	79.2558	-0.95576
183	83.6000	84.8643	-1.26429
184	80.8000	81.7128	-0.91282
185	80.4000	81.1819	-0.78192
186	77.4000	77.9904	-0.59037
187	77.8000	78.7137	-0.91366
188	84.4000	85.4785	-1.07846
189	81.2000	82.3613	-1.16127
190	78.6000	79.2304	-0.63041
191	78.1000	78.8259	-0.72585
192	78.9000	80.3306	-1.43063
193	77.3000	78.4403	-1.14032
194	73.2000	73.6294	-0.42938
195	78.4000	79.5917	-1.19168
196	75.4000	76.5793	-1.17930
197	77.1000	78.3259	-1.22585
198	75.9000	76.7032	-0.80325
199	75.0000	75.2753	-0.27531
200	73.0000	73.5314	-0.53141
201	76.9000	78.1843	-1.28427
202	75.5000	76.7232	-1.22318
203	75.5000	76.1590	-0.65896
204	74.7000	74.5957	0.10426

-- stop

APPENDIX C

SOCIAL SURVEY QUESTIONNAIRE

University of Bath

COMPUTER NO.	

School of Architectural and Building Engineering

Traffic Noise Annoyance Questionnaire

1	2	3	4

Name ....Serial No. ....
Address ....
No. of Junction ....Site No. ....
Time of Interview ....Date ....Day of Week ....

Introduction and Survey objective to establish a rapport
between interviewer and subject

PART ONE

(i) Traffic Noise Level:

Q.1. How long have you been living at this particular address? [5]

over 6 months - up to 12 months	1
over 1 year - up to 5 years	2
over 3 years - up to 10 years	3
over 10 years - up to 15 years	4
over 15 years	5

Q.2. In general, how satisfied are you with this area as a place to live? [6]

very satisfied	1
fairly satisfied	2
no feeling either way	3
a little dissatisfied	4
very dissatisfied	5

Q.3. In this particular address are you satisfied with the following things?

	1	2	3	
	Yes	No	Don't know	
1. The level of noise in the area				7
2. Closeness of shops, schools and parks				8
3. The people in the area				9

Q.4. Which of the following things do you dislike most about this area ?

1. Traffic Noise		10
2. Road Traffic in General		11
3. Exhaust Fumes		12
4. Traffic Accidents		13
5. Pedestrian Difficulty		14

Q.5. What sort of noise do you notice most around there?

1. Traffic Noise		15
2. Ambulance Noise		16
3. Fire Engine Noise		17
4. Train Noise		18
5. Building and Road Maintenance Noise		19
6. People Noise		20

Q.6. (SHOW CARD A)
When you are a pedestrian outside this building, would you tell me which number on the scale best describes how you feel about the traffic noise conditions ?

21

Definitely Satisfactory	Just Noticeable	Moderate	Noisy	Definitely Unsatisfactory
1	2	3	4	5

Q.7. How do you feel about the amount of noise from traffic when you are inside this building ?

22

Definitely Satisfactory	Just Noticeable	Moderate	Noisy	Definitely Unsatisfactory
1	2	3	4	5

(ii) Traffic Noise Sources

Q.8. (SHOW CARD B)
Looking at this card would you tell me which number best describes how you feel about the following sources of traffic noise?

23

(8.1) Cars

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(8.2) Buses and Coaches

24

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(8.3) Heavy Lorries

25

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(8.4) Motor Cycles

26

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

Q.9. Does noise from the following factors annoy you in any way ?
(SHOW CARD B)

(9.1) Nearest junction
(Traffic light/Roundabout/
Priority Junction)

27

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(9.2) Accelerating Vehicles

28

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(9.3) Squealing Tyres

29

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(9.4) Interrupted traffic flow

30

Not at all Annoyed	Just Noticeable	Moderate	Annoyed	Extremely Annoyed
1	2	3	4	5

(iii) Traffic Noise Disturbance

Q.10. Do you get any vibration in this building from the traffic?

31

Yes 1
No 2

(If yes go to Question 11)

Q.11. Does vibration bother you?
(SHOW CARD C)

32

Never	Sometimes	Often	Very Often	All the Time
1	2	3	4	5

Q.12. Do you have any double glazing or sound insulation on the roadside facade?

33

Yes 1
No 2

Q.13. (SHOW CARD C)
How often do you have to shut your windows because of the traffic noise?

34

Never	Sometimes	Often	Very Often	All the time
1	2	3	4	5

Q.14. How often does the noise still disturb you when the windows are shut?
(SHOW CARD C)

35

Never	Sometimes	Often	Very Often	All the time
1	2	3	4	5

Q.15. Does traffic noise make you feel uncomfortable ?

36

Yes 1
No 2

Q.16. Do you have difficulty falling asleep at night?

37

Yes 1
No 2

Q.17. (SHOW CARD C)
How often does the traffic noise disturb your sleep ?

38

Never	Sometimes	Often	Very Often	All the time
1	2	3	4	5

Q.18. Does traffic noise cause you to occupy the rear part of the building away from noise?
(SHOW CARD C)

39

Never	Sometimes	Often	Very Often	All the time
1	2	3	4	5

Q.19. (SHOW CARD C)
When indoors. does traffic noise ever cause :

(19.1) interference with T.V. and listening to the radio

40

Never	Sometimes	Often	Very Often	All the Time
1	2	3	4	5

(19.2) interference with conversation

41

Never	Sometimes	Often	Very Often	All the Time
1	2	3	4	5

(19.3) Interference with concentration | 42

Never	Sometimes	Often	Very Often	All the Time
1	2	3	4	5

Q.20. What time of day does traffic usually bother you ?

20.1 Morning peak hours (7 a.m. - 9 a.m.)		43
20.2 Day time		44
20.3 Afternoon peak hours (4 p.m. - 7 p.m.)		45
20.4 Evening (7 p.m. - 10 p.m.)		46
20.5 Night time (10 p.m. - 7 a.m.)		47

Q.21. When does traffic noise usually bother you ?

21.1 Week day		48
21.2 Weekend		49
21.3 Friday night		50
21.4 Other times		51

Q.22. Do you feel traffic noise has reduced the financial value of your property? (SHOW CARD D)

52

Not at all Reduced				Very Much Reduced
1	2	3	4	5

Q.23. What is the total number of occupants of this building ? ....

53

Q.24. Is there anything else about traffic which bothers you here?

....

....

....

END OF INTERVIEW

PART TWO

The following can be completed outside by the interviewer:

Computer No.	

(i) Principal information

1	2	3	4

Q.1. Sex:

1	2
Male	Female

5

Q.2. Approximate Age:

1	2	3
18-39	40-59	60+

6

Q.3. Land Use

7

1	2	3	4	5
Main route	Office	Shopping	Residential	Open Space

Q.4. Type of Junction

8

1	2	3
Traffic Light	Roundabout	Priority Junction

Q.5. Type of Building

9

1	2	3	4
Flat	Terrace	Detached or Semi-Detached	Other

Q.6. Floor No.

10

1	2	3
Ground	First	Second

(ii) Variables

Q.7. Independent Variables:

7.1 Distance from the middle of building front and the nearest junction (m).		11
7.2 Distance of building facade from nearest kerbside (m).		12
7.3 Road width (m).		13
7.4 Distance of farside facade (m).		14
7.5 Mean Speed (km/h)		15
7.6 Traffic Flow (v/h)		16
7.7 Percentage of medium and heavy vehicles (%)		17
7.8 Number of light vehicles (v/h)		18
7.9 Number of medium vehicles (v/h)		19
7.10 Number of heavy vehicles (v/h)		20

Q.8. Noise Level Values dB(A)

8.1 L_{10}		21
8.2 L_{50}		22
8.3 L_{90}		23
8.4 L_{eq}		24

Q.9. General Comments:

Q.10 Sketch of the location of subject address:

APPENDIX D

PUBLICATIONS RESULTING FROM WORK DESCRIBED IN THIS THESIS

The following papers have already been published or accepted by the journals and conferences listed:

Appendix D1	'A Computer Model to Assess and Predict Road Transport Noise in Built-up Areas'. **Applied Acoustics** (An international journal), **Special Issue** on Noise from Road Traffic, Vol.21, 1987.
Appendix D2	'Prediction Models for Road Traffic Noise (L_{eq}) in Restricted Flow Situations'. **Noise Control Engineering Journal** , USA, 1987.
Appendix D3	'Can Noise Generation from Road Transport be Abated by Design and Planning?'. Proceedings of the, 1987 Spring Conference, Institute of Acoustics (**Acoustics '87**), Portsmouth (UK), 1987, Vol.9: Part 3, pp.295-302.
Appendix D4	'Factors Contributing to Traffic Noise Annoyance'. Proceedings of the 1987 International Conference on Noise Control Engineering (**inter-noise '87**), Beijing (China), Sept. 1987.
Appendix D5	'Estimation and Modelling of Traffic Noise in Urban and Suburban Environments'. Proceedings of the, 1986 Spring Conference, Institute of Acoustics (**Acoustics '86**), Salford (UK), 1986, Vol.8:Part 3, pp. 267-273.

Appendix D6 'Prediction Techniques for Road Transport Noise (L_{eq}) in Built-up Areas'. Proceedings of the 1986 International Conference on Noise Control Engineering (**inter-noise '86**), Cambridge (USA), July 1986, Vol. 1, pp. 221-227.

Appendix D7 'Traffic Noise Annoyance Near Road Junctions'. Proceedings of the 6th Symposium of the Federation of the Acoustical Societies of Europe (**FASE '86**), Sopron (Hungary), Sept. 1986.

Appendix D8 'Social Response to Noise from Interrupted Traffic Flow'. Proceedings of the, 1985 Spring Conference, Institute of Acoustics (**Acoustics '85**), York (UK), 1985, Vol.7:Part 2, pp. 383-390.

Appendix D9 'Urban Road Traffic-Noise Level Prediction'. Proceedings of the 4th Congress of the Federation of the Acoustical Societies of Europe (**FASE '84**), Sandefjord (Norway), Aug.1984, pp. 269-272.

Appendix D1

'A Computer Model To Assess And Predict Road Transport Noise In Built-Up Areas'. Applied Acoustics, Special Issue, Vol. 21, 1987.

ABSTRACT

A new computer model is presented for predicting road transport noise in urban and suburban areas under non-free flowing traffic conditions. The model utilizes empirical expressions developed from field studies made at 204 sites (2448 thirty minute samples) in Bath. The model takes into account a large number of basic variables, namely: traffic flow, speed and composition (3 classes of vehicles), percentage of heavy and medium vehicles, distance from surrounding building facades, and distance from various junctions (3 categories). The 'descriptive variables', such as classification of land use, type of junctions and characteristics of traffic are also considered. The input variables were selected deliberately to facilitate the eventual use of the model for design and land use planning purposes. A good level of agreement has been achieved between measured and predicted values. L_{10}, L_{50}, L_{90} and L_{eq} dB(A) were employed. The model is an adequate tool for thorough and detailed environmental schemes.

Appendix D2

'Prediction Models For Road Traffic Noise (L_{eq}) In Restricted Flow Situations'. NCE Journal, USA, 1987.

ABSTRACT

In addition to their performance limitations, current prediction models of noise from non-free flowing traffic have given little attention to L_{eq}.

This study set out to use noise L_{eq} dB(A) from urban and suburban non-free flowing traffic, and the parameters which characterise the environment, affect noise levels and are necessary to the work of designers and planners. Based on a survey in the City of Bath, five predominant land uses were defined at 204 sites chosen to give a representative sample of traffic conditions for each of these five types. Thirty-minute noise level recordings were made hourly at each site between 7.00 and 19.00 hours, and the independent variables of interest were recorded simultaneously. Three prediction models were then developed, relating noise to the variables commonly used. Two of the final models are expressed in terms of L_{eq} dB(A), and locations of farside and nearside building facades, traffic flow, speed and composition (3 classes of vehicles), percentage of medium and heavy vehicles and distance from considered junctions (i.e traffic lights, roundabouts and priority junctions. The third model relates L_{eq} to L_{50}, L_{10} and L_{90}. The models are comprehensive, accurate and practical in order to save time and money.

Appendix D 3

Proceedings of The Institute of Acoustics

CAN NOISE GENERATION FROM ROAD TRANSPORT BE ABATED BY DESIGN AND PLANNING ?

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INTRODUCTION

A great public awareness of the traffic noise problem has resulted in greater efforts to decrease its effects in recent years (1). This is reflected in the current imposition of motor vehicle noise emission standards and noise exposure regulations at national and international level. While there is slow development in minimising vehicle noise at source, road and building designers and planners can no longer carry out their work according to economic and traditional geometric elements alone. They must also consider such environmental factors as noise. It is necessary to minimise the extent of the noise problems, and also to develop standards of planning and design objectives, especially in built-up contexts, where knowledge is particularly incomplete.

This paper deals with the evaluation of the most appropriate means of traffic noise control in urban and suburban areas, and reports the noise prediction models developed by the author for various urban and suburban purposes. Fig 1 shows the typical elements of noise control.

SOURCES OF TRAFFIC NOISE

The principal sources of traffic noise in built-up situations are those due to many vehicles, consisting of a combination of individual noise generators and travelling at changeable speeds and in varying conditions through various road configurations surrounded by buildings. Such noise is also associated with interruptions in traffic flow caused by various types of junctions. In general, the origins of motor vehicle noise fall into two distinct categories, firstly, power system noise which relates to engine speed, and secondly, coasting noise which relates to road speed. The noise from the power system is mainly generated by the fan and engine. Coasting noise originates mainly from tyre-road contact and wind. The relative importance of these various noise generators depends on the maximum produced dB(A) noise level. Thus the noise of major sources must be reduced to minimise the total vehicle noise.

It is twenty-five years since the well known studies, such as that in Britain (2,3), were carried out to examine the problems of road vehicle noise, and a remarkable number of recommendations were issued to limit the maximum emitted noise level (4). But the results of this development can be summarised in three points. Firstly, there has been a 4dB(A) reduction of goods vehicle noise levels in accordance with European regulations, from 92 to 88 dB(A). Secondly, the hope for lorries with maximum noise levels of 80 dB(A) is still a projection for the next decade (5). Thirdly, there is no feasible alternative (e.g. electric vehicles) to vehicles with internal combustion engines. The main reason is that the possibility of attenuation of motor vehicle noise at source is dependent on a number of complex situations. These include:

1. The available technology.
2. International agreement.
3. Vehicle markets and user demands.
4. Problems of vehicles already in use.
5. The accompanying increase in cost of new quiet vehicles.
6. Competition between motor companies.
7. Economic status of motor industry.
8. Development in current motor vehicle plants.
9. Time needed.
10. Identification of acceptable noise levels.
11. Price and availability of oil.
12. Difference in measurement methods for acceptable vehicle noise limits.

Taking into account the slow progress in this area during the years and considering the above situations, it is doubtful that any radical change will be fully perceived before the year 2000. The alternative, therefore, is to work during the design and planning procedures on traffic noise-reducing features, through the path and receiver, to reduce noise exposure and noise annoyance.

DESIGN AND PLANNING

The future of road transport is beyond doubt; in spite of the resulting deterioration of the environment. Great efforts, therefore, must be made in order to estimate how the better use of motor vehicles can be achieved and how the traffic noise problem can be overcome.
The increasing public awareness of the drawbacks of vehicular traffic and the enforcement of noise exposure regulations has put pressure on city engineers and planners to consider noise with the traditional parameters in their plans, in order to be able to evaluate existing and future environmental changes. In other words they have to prevent noise from being transmitted from source to receiver (i.e. people). So the design procedures of roads and buildings, and planning for separation of noise generation and noise-sensitive developments are effective measures which should be employed to a greater extent for decreasing the negative influences of road traffic noise in urban and suburban areas. The following points illustrate the advantages of considering noise at the planning and design stages.

CAN NOISE GENERATION FROM ROAD TRANSPORT BE ABATED BY DESIGN AND PLANNING ?

1. People in their daily life are subject to traffic noise emitted by streams of vehicles, rather than by specific individual vehicles.

2. Traffic noise levels are dependent on those features found in built-up areas. Thus, it is best to modify the features which contribute to the high level of noise.

3. Recent government regulations (6) allow compensation to be paid in terms of either a cash grant or insulation to appropriate members of the public who are exposed to road traffic noise above specific levels.

4. Existing vehicle noise limits are subject to available technology and other factors, while the acceptable traffic noise limits must be determined (usually by combined physical and social surveys) according to the adverse effects that noise produces in everyday routine operations.

Planners and designers, therefore, cannot wait an indefinite period for the inception of quiet transport, and the appropriate method to hand is to modify the features which are responsible for the propagation of the noise and also to isolate the receiver.

TRAFFIC NOISE ABATEMENT

It is practical to protect the environment (people in and around buildings) from the unwanted traffic noise in urban and suburban areas by means of the following:

1. Transportation Planning: At this stage there are three distinct levels at which noise evaluation needs to be considered. Firstly, long-term planning which usually looks ahead some 15 years. Secondly, road network position. At this stage a more detailed evaluation of the best alternative is required. Thirdly, network design. At the first two levels the scheme and its suitable position have been identified. At this third level detailed design and specifications of each road section are required. Simple and reliable noise prediction methods are needed for the first two stages, while the final stage demands a comprehensive tool.

2. Road Building: The benefit of new road schemes usually results from the movement of traffic in a more convenient way, e.g. lorries which had no alternative but to run on specific roads, causing noise annoyance, can operate in other directions.

3. Traffic Management: This is also a powerful means of attaining a better environment, e.g. by the separation of networks with light from those with heavy traffic.

4. Urban Planning: This is another course of action for a better environment, e.g. separation of industrial and residential areas.

5. Building Structure: This involves location, use, design and insulation of buildings (1). The preliminary evaluation of building location requires a simple prediction tool.
Points 2-5 above require the availability of thorough and reliable noise prediction methods.

PREDICTION METHODS

Prediction methods, therefore, have become more important as tools to be implemented for minimising 'unwanted sound'. Their main advantages are to be found in the saving of time and money, and in avoiding field measurements which require skill and expensive equipment. They give the decision-makers freedom to create the best system in terms of safety and comfort for the public. It is convenient also to have prediction tools which rely on existing transportation engineering methods.

However, existing prediction methods for noise from non-free flowing traffic, which usually operates in built-up areas, showed several limitations (7). This is due to the large number of contributory factors. There is also insufficient knowledge of people response to noise. An attempt has been made by the author to fill some of the gaps by establishing prediction models for various design and planning purposes, based on a wide-ranging programme of physical and social surveys. These surveys covered 3530 thirty-minute noise level measurements at 266 sites, including 23 signalised intersections, 6 roundabouts and 15 priority junctions. The sites also covered 6 categories of land use, 3 types of traffic conditions and 40 dependent and independent variables, in addition to the answers given by a sample of people to a questionnaire. The development models can fall into two families.

1. Simplified Models:
This group includes models in the form of equations (8,9,10). The models relate noise levels, L10, L50, L90 and Leq dB(A) to: traffic speed (V km/h); distance of farside facade (Fm) and nearside facade (Nm); distance of junctions (Jm); traffic composition (C v/h); traffic flow (Q v/h); and percentage of medium and heavy vehicles (P%). They are for urban conditions (v=48km/h) and for urban and suburban conditions (v=10-75 km/h).
Overall Traffic Noise Annoyance Index OTNAI, a scale for assessing the effects of noise, was also established by the author (11,12). It is the average of 19 response scores on a 5-point scale, and represents the essential factors of noise annoyance, e.g. classes of vehicles, junctions, indoor noise, and interference with people's activities. A prediction models were then issued relating OTNAI to L10, L50 and Leq dB(A).

The above models can provide rapid prediction of the anticipated noise exposure based on 'basic variables', and also prediction of noise annoyance. Such evaluation is needed for everyday requirements and early planning and design stages, e.g. the stage of long-term transportation planning. The models are simple, accurate and based on common variables.

2. Detailed Models:

This family includes a comprehensive computer model and graphic computer model (13). The difficulty of covering all the related variables mathematically necessitated the establishment of a new computer model to assess and predict road transport noise and noise annoyance under a variety of urban and suburban conditions. Apart from the 'basic variables', the model also considers the 'descriptive variables', e.g. land use. The model covers almost all the variables of built-up environments. It is designed to assess 2000 sites at each run, but the user may change the 2000 if a larger number is considered. A graphic computer model was also developed to evaluate any scheme by modifying the individual variables. The graphic model estimates 170 probabilities at each run associated with 29 figures. Both models utilised the aforementioned simplified models and proved their validity. They are an appropriate tool for a thorough and detailed policy, e.g. enviromental planning for urban areas.

EXAMPLE

The relationship between estimated noise exposure and annoyance with changes in traffic composition was examined. The investigation was associated with various percentages of medium and heavy vehicles, since these vehicles contribute to the high level of noise.

Two typical roads were selected as an example here and the results are given in Table 1, which shows how variation in the percentage of medium and heavy vehicles affects the level of traffic noise and the estimated OTNAI. It is obvious that tremendous changes are required in the structure of traffic to achieve significant improvements in the overall level of noise and to minimise public reaction. For example, reduction of P from 10% to 5% on an urban main road would result in only a 0.91 dB(A) reduction in noise exposure level, and 0.16 in OTNAI. Even in the cases where P=0, the level of noise still exceeds the official recommended level (e.g. the recommended British level is L10 = 68 dB(A)).

The above investigation indicates that people's annoyance will continue even if there are no vehicles which are individually noisy. This means that the traffic noise problem cannot be abated solely by minimising the noise emission of heavy lorries, which are the target of current programmes in many countries. So an effective noise policy in any urban and suburban area would require consideration of the total road traffic noise level and its variables as they operate in real situations, to satisfy public demand. This policy can be executed through the processes of design and land use planning.

Road	Q v/h	P %	Predicted L10 dB(A)	Predicted OTNAI
Urban main Road		0	79.89	3.481
V = 33 Km/h		5	80.81	3.642
J = 78.6m (Traffic light)	2750	10	81.72	3.800
N = 2.3m F = 15.8		20	83.55	4.120
Office area Road		0	78.25	3.190
V=18.99Km/h	1200	5	79.20	3.360
J = 37m (Traffic Light)		10	80.10	3.520
N = 3.3m F = 10.80m		20	81.91	3.830

Table 1 Effect of changes in the percentage of medium and heavy vehicles on the predicted noise level and noise annoyance (Based on L10 urban and surburban conditions model and annoyance model)

SUMMARY

While there is slow progress in minimising vehicle noise at source, it is increasingly important to have adequate methods of traffic noise prediction, so as to abate it by means of design and planning. Neither limiting vehicular traffic nor increasing the distance between buildings and the road network are easily achievable in built-up contexts. Application of the developed noise exposure and noise annoyance models has shown that a comprehensive policy would be the most convenient protection

against traffic noise disturbance. This must include consideration of traffic noise in the processes of transportation planning, road building, traffic management, urban planning and building construction.

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I would like to acknowledge the help and assistance that I received from Dr D.J. Croome (Reader) of the School of Architects and Building Engineering at Bath University. Thanks are also due to Mr W. Powell for the advice that I received. Sincere gratitude to Professor E. Happold (Head of School), Professor M. Brawne and their staff for their assistance during the period of the study.

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CAN NOISE GENERATION FROM ROAD TRANSPORT BE ABATED BY DESIGN AND PLANNING ?

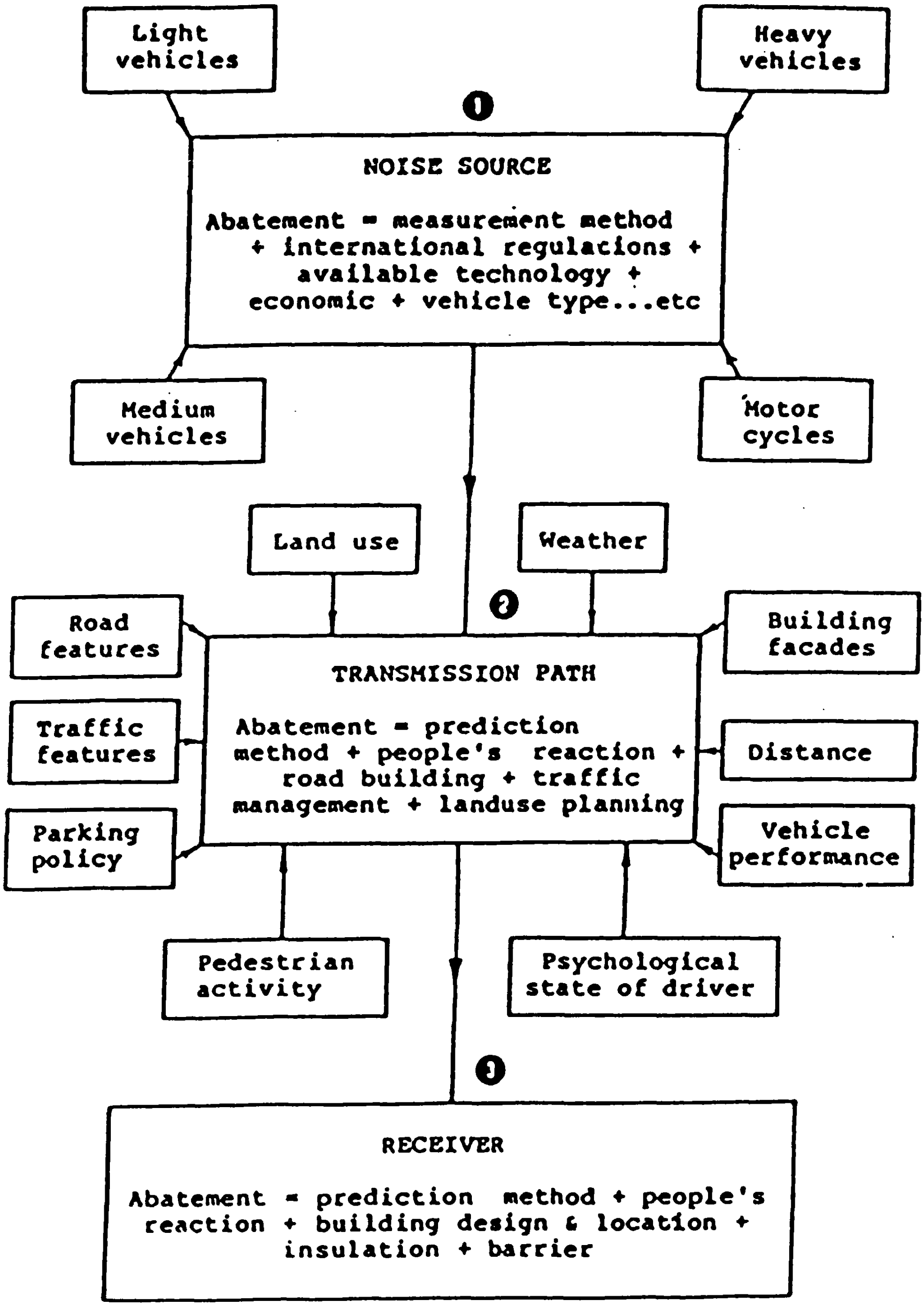

Fig 1 Elements of traffic noise control in built-up areas

Appendix D4

'Factors Contributing To Traffic Noise Annoyance'.
inter-noise '87, China, 1987.

ABSTRACT

No longer can road and building designers and planners do their work according to economic and traditional geometric elements alone. They must also consider such environmental factors as traffic noise annoyance. It is necessary to estimate the extent of the noise problem according to people's judgements, and also to develop standards for planning and design objectives, as knowledge in this field, especially in built-up areas, is incomplete. These aims can be achieved by studying the reaction of the public to traffic noise and its causes.

This paper investigates the attitude of people towards the environment in the urban area of Bath, where the flow of traffic is non-free. It consists of an examination of the answers to a questionnaire which was applied to a sample of the population. It also deals with the development of new prediction models which relate the Overall Traffic Noise Annoyance Index (OTNAI) to noise exposure indices L_{10}, L_{eq} or L_{50} dB(A). The OTNAI was established as the average value of 19 response scores (on a 5-Point scale) given in answer to the questionnaire. It represents noise sources, e.g classes of vehicles, acceleration and presence of junctions; level of propagated noise, e.g indoor and outdoor noise levels; interference with people's activities, e.g sleep, concentration and conversation. The prediction models gave a high level of correlation such as R = 0.84 with L_{10}.

The employment of noise annoyance models and noise exposure models (the latter were defined in other parts of the research) has shown that a

comprehensive traffic noise abatement policy, through the design and planning process, would be the most convenient protection against traffic noise disturbance, since the noise problem cannot be minimised solely by the control of heavy vehicle noise and progress in attenuation of vehicle noise at source has been very slow during the past years.

Appendix D 5

Proceedings of The Institute of Acoustics

ESTIMATION AND MODELLING OF TRAFFIC NOISE IN URBAN AND SUBURBAN ENVIRONMENTS

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INTRODUCTION

Road transport has always been and continues to be an essential ingredient of the progress of civilization. During the last few decades, the rapid increase of motor vehicle use and ownership, together with population growth and the attraction of people into urban and suburban regions for work and leisure has set in motion development that has led to a modern society in which traffic noise seems to be an inevitable problem. Thus, the importance of traffic noise as one of the design parameters for planners, building and road designers and traffic engineers has increased tremendously [1, 2 and 3].

When dealing with noise and its control, three components need to be considered: first, the source of the noise; second, the path along which the noise travels; and third, the receiver. In the case of traffic noise in urban and suburban environments the source is various kinds of vehicles travelling at different speeds and conditions through areas of various types of land use and road layout. The transmission path is the direction taken by the sound waves, while the receiver may be any subject who works or lives in the area. Of course, the best method of decreasing the effects of traffic noise is the abatement of vehicle noise at source. But this option is not one over which the planners and city engineers have control. Besides, it is now over fifteen years since traffic noise was identified as the predominant source of annoyance in Europe [4], and the markets have not yet witnessed vehicles whose noise is reduced by 10 dB(A) as recommended. Despite some successful trials, the operation of large numbers of quiet vehicles for general purposes is still a hope for the next decade [5]. The reason is that this situation is always dependent on many complex factors such as available technology, international legislation and the economic status of the country.

This paper deals with the abatement of traffic noise through planning and design. The target is a reliable model which can be implemented by planners and city engineers to forecast and evaluate noise levels arising from interrupted traffic flow in urban and suburban areas. A suite of computer programs has been evolved based on a variety of field measurements at 204 locations in Bath. It enables L_{10}dB(A) value to be determined in terms of all the essential parameters and gives results which are comprehensive, accurate and practical.

MODELLING OF TRAFFIC NOISE

Various types of forecasting methods have been utilized up until now. The main approach is to use them in the design and planning stages in place of field measurements. This has several advantages, namely, it saves time and money. Prediction methods give the decision-maker freedom to modify any variable in order to create the best system whilst avoiding unusual traffic congestion (e.g. due to maintenance or accidents) which may affect the accuracy of field measurements. Finally, it is convenient to have a prediction tool which relies on existing transportation engineering methods.

In general, prediction models fall into two areas: those for freely and those for non-freely flowing traffic. Given traffic and road parameters, models have been developed which forecast noise from freely flowing traffic and involve a number of variables including high speed traffic and steady noise levels. For non-free flowing traffic in built-up areas the models deal with several factors such as low speeds, changeable noise levels, and junctions. Traffic noise may be predicted by use of empirical, scale or theoretical models. The empirical model is usually constructed on the basis of real field investigation, using the multiple regression analysis method [6] and is widely used; most of the current prediction methods are based on such models for free flowing and non-free (with limitations) flowing traffic [7 and 8]. Scale models have been introduced as an instrument to assess the importance of specific parameters without the need for field measurements [9]. Yet the use of scale models in estimating the absolute levels of traffic noise is limited. Theoretical models are usually based on statistical distribution of noise and independent parameters or computer simulation models [10]. Apart from computer models for vehicle noise in the vicinity of traffic lights, there are no comprehensive theoretical methods in the field of non-free flowing traffic in built-up situations.

Noise from non-free flowing traffic depends on the specific driving needs of vehicles, such as accelerating and decelerating, which predominate near junctions. This complex situation has not been modelled properly. Existing methods for noise from restricted traffic flow have neglected many of the design parameters [11] and show the following limitations:

1 - <u>Speed of traffic</u>: In urban areas, speed is significant in studies connected with theory of traffic flow, road designs, traffic management schemes, signs and signals, markings and speed limit.
2 - <u>Presence of junctions</u>: Again in built-up situations, junctions are the most important single consideration in any urban road design and in land use planning.
3 - <u>Existence of surrounding building facades</u> (especially those on the farside): In built-up areas, road networks are usually surrounded on both sides by buildings of various use which have an influence on the level of propagated noise due to multiple reflections.

In addition, the studies have been based on a small number of field sites which only represent a limited number of built-up area conditions, e.g. traffic lights [10].

ESTIMATION AND MODELLING OF TRAFFIC NOISE IN URBAN AND SUBURBAN ENVIRONMENTS

BASIS OF THE COMPUTER PROGRAMS

NFNOS, UBSUB and GRUBS form a Suite of Programs designed to forecast traffic noise arising from non-free flowing traffic in urban and suburban areas for planning purposes. The programs deal with most of the parameters which characterise the structure of built-up areas, affect noise levels and are included in design standards. In designing these models the task was to permit prediction in as many cases as possible, so a wide range of field measurements were carried out. Six predominant land uses were defined at 204 sites chosen to give a representative sample of traffic conditions for each of these six types. Thirty-minute noise level recordings were made hourly at each site between 7.00 and 19.00 hours. Other variables of interest were recorded simultaneously.

The distance between kerb and receiver was one metre, with a microphone height of 1.2m. The building facades were continuous on both sides. Noise from the traffic stream was a predominant problem in all locations. The sites were selected to represent various kinds of junctions so that accelerating and decelerating traffic could be considered but only level stretches of road were taken into account. Three separate programs were designed to meet the following goals:

1. To identify those variables that affect the environment significantly.
2. To predict noise levels.

COMPONENTS OF THE PREDICTION MODELS

In built-up areas there are huge numbers of physical constraints controlling the flow and speed of traffic [12] and of these the following factors are used in the study:

1. <u>The road system</u>: The study was carried out along various road networks. Road width (W) ranged from 6m to 18m and 43 junctions were considered. The junctions covered were roundabouts, priority junctions and traffic lights. One and two way traffic were included. Noise levels L_x dB(A) at one metre from the traffic stream and distance (J) from various kinds of junctions have been shown to be of the form (up to 250 m):

$$L_x = a_0 - a_1 J \tag{1}$$

where a_0 and a_1 are empirical constants and J ranged from 4 to 420 m.

2. <u>Traffic variables</u>: The vehicles in the traffic stream were divided into three categories [13]; light (L), medium (M) and heavy (H). Again noise level with traffic flow (Q), percentage of heavy and medium vehicles (P), and mean speed (V), have been shown to be of the form:

$$L_x = a_2 + a_3 \lg Q \tag{2}$$

$$L_x = a_4 + a_5 P \tag{3}$$

$$L_x = a_6 - a_7 \lg V \tag{4}$$

where a_2-a_7 are empirical constants. Traffic flow ranged from 284 to 3000 v/h, depending on site and time. P was between 0 and 20% while speed was between 10 and 75 km/h, despite the speed restriction of 48 km/h (urban) and 64 km/h (suburban).

3. Building locations: Buildings flanked the roads on both sides. Noise levels with distance of measurement point from nearside facade (N) and distance from farside facade (F) have been shown to be of the form:

$$L_x = a_8 - a_9 \lg N \tag{5}$$

$$L_x = a_{10} - a_{11} \lg F \tag{6}$$

where a_8-a_{11} are empirical constants. N ranged from 1.5 to 24 m whilst F from 9.35 to 37.5 m.

4. Noise units: Traffic noise is generated by a number of vehicles of different specifications being driven under changing conditions through various roads surrounded by areas of different land use classifications. For studying this noise, L_{10} dB(A) was considered during the course of study, where L_{10} is the basis for government regulations and design guides dealing with traffic noise in Great Britain . It also correlates well with human reactions defined by another part of this study [14].

5. Other variables were considered such as number of lanes; condition of road surface; traffic conditions, characteristics and directions and weather conditions.

PROGRAM DEVELOPMENT

NFNOS Program: This program uses a statistical computing system [6] to establish a prediction formula, based on multiple regression analysis. The following equation summarises the finding, based on the field study data:

$$L_{10} = 58.6 - 5.99 \lg V + 11.4 \lg Q + 0.183 P - 5.94 \lg F - 0.0102 J - 2.46 \lg N \tag{7}$$

This model is expressed in terms of the most effective parameters. It gave a good correlation coefficient R=0.969, standard deviation, 0.770 and accuracy prediction with $\pm$ 1.8 dB(A). The model has the following advantages:

1. It is a practical way of saving time and money and avoids the need for field measurement.

2. It is simple and easy to understand by City Engineers who may have a

limited knowledge of acoustics but are in a position to consider traffic noise.

3. It is based on real field data which covered various situations.

4. It uses variables that are necessary for design purposes.

5. It provides rapid prediction to an accuracy appropriate to the planning process, based on the fundamental parameters.

UBSUB Program: Field investigation and the development of the above model has provided significant data necessary for assessment of road design and location for enviromental planning. Thus, in order to estimate more complex situations than can be introduced by theory alone, and because of the difficulty of including all the parameters in one formula, the presentation of UBSUB as a comprehensive computer program was required. The program is designed to compute noise levels in terms of most of the parameters which formalise the environment. Input data are required describing road, traffic and propagation features and land use classification. The program is written in the FORTRAN language and the output is in the form of a printed report containing predicted noise level values, mean and range of variables, and identification of land use, junctions and traffic circumstances (see Table 1). The advantages of the model are:

1. It predicts noise levels with regard to a large number of variables.
2. It is based on a thorough investigation of real sites.
3. Noise level and other parameters in built up areas are subject to change from time to time and this model has the flexibility to incorporate these variations.
4. The program is written in a common computer language and it could be run or transferred to any system.
5. It uses variables that are necessary for design and land use planning, and are easily obtainable.
6. It provides detailed data which cannot be covered by one method such as Equation 7. Thus it is a tool which may aid the planner in assessing the development of built-up areas involving a variety of conditions.

GRUBS Program: This is a graphic program which takes the input information from the formulae of the last program and introduces a graph, to allow for the estimation of the variables which are required to predict levels of noise. The main objective of this program is to modify any variable in order to maintain the acceptable level of noise. The computer program was developed utilizing the Gino graphic facilities at Bath University computer system.

SUMMARY

The increasing importance of noise effects in built-up areas has not been matched by the development of a comprehensive prediction model for assessing its significance. This study set out to use noise from urban and suburban traffic and the parameters which characterise the structure of built-up areas, influence environmental noise and are necessary for the work of designers and planners. Three models for prediction of noise levels were proposed. An empirical model which provides rapid prediction is suggested that enables the L_{10} dB(A) value to be determined in terms of principal variables. A comprehensive computer model has also been designed that enables L_{10} dB(A) value to be obtained based on a large number of variables. A graphic model has been established to assess the value of parameters related to predicted noise levels. Also, a modification has been made to the UBSUB computer model to allow a variety of design parameters and conditions to be employed [15, 16 and 17].

The techniques have been formalised to aid planners and designers in assessing and controlling the noise impact from non-steady traffic, in order to implement partial or total road network development, using easily obtainable urban and suburban parameters. These techniques will enable a reliable environmental policy to be established which includes traffic management, road and building design and land use planning.

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Table 1. Typical Output of UBSUB Computer Model

1. Noise Values dB(A)

Total Site Nos. = 3

Site No.	Predicted L10	Actual L10
1	83.44	84.50
7	79.77	79.40
104	70.53	70.60

2. Mean Values of the Variables

V = 29.87 km/h　　H = 29.3 v/h

L = 1519.33 v/h　　Q = 1691.30 v/h

M = 142.67 v/h

3. Mean Values of the Predicted Noise Levels

$L_{10} = 77.91$

4. Range of Variables

Parameters	max	min	Parameters	max	min
V	38.96	24.00	N	5.40	2.10
L	2277.00	260.00	J	113.40	25.00
M	213.00	10.00	Q	2526.00	284.00
H	52.00	0.00	P	11.30	3.75
W	9.90	8.00	F	16.00	13.00

5. Range of Predicted Noise Levels

Parameters	max	min
L10	83.44	70.53

6. Distribution of Measurement Locations

1. Height of measurement = 1.20 m
2. Distance between measurement point and nearside kerb = 1.00 m
3. No. of light traffic sites = 0
4. No. of medium traffic sites = 1
5. No. of heavy traffic sites = 2
6. No. of accelerating traffic sites = 3
7. No. of decelerating traffic sites = 0
8. No. of one-way traffic sites = 1
9. No. of two-way traffic sites = 2
10. No. of two lane sites = 3
11. No. of four lane sites = 0
12. No. of more lane sites = 0
13. No. of asphalt road surface sites = 3
14. No. of concrete road surface sites = 0
15. No. of traffic lights = 1
16. No. of roundabout = 0
17. No. of priority junction = 1
18. No. of residential area sites = 0
19. No. of office area sites = 0
20. No. of shopping area sites = 1
21. No. of urban main route sites = 2
22. No. of suburban principal route sites = 0
23. No. of rainy weather sites = 0
24. No. of dry weather sites = 3
25. No. of windy weather sites = 0

Appendix D 6

inter-noise
Cambridge, USA
1986 July 21-23 86

PREDICTION TECHNIQUES FOR ROAD TRANSPORT NOISE (Leq)
IN BUILT UP AREAS

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INTRODUCTION

The tremendous increase in motor vehicle use, together with widespread road networks, have resulted in considerable problems of road traffic noise, especially in highly populated areas. This situation puts pressure on City Engineers and Planners to include noise as one of the parameters in their plan in order to be able to evaluate existing development and future change (1 and 2). For these reasons, the need for a prediction tool to aid in the early planning stage has become urgent. Such a design aid would help to avoid the need for field measurements which cost time and money.

Over the past twenty years most of the Prediction methods have been related to noise from high speed freely flowing traffic on road networks which were unflanked by buildings. With regard to noise from non-free flowing traffic in built-up areas the situation is more complex. In this case, normally the buildings are sufficiently close to the side of roads and hence cause noise reflection. Noise also depends on specific driving needs of vehicles as well as traffic lights and signs which are used to control traffic flow and speed. Yet this complex situation has not been modelled properly. However, attempts have been made in many countries to develop reliable prediction techniques but existing methods show several limitations (3 and 4). Of these, they have neglected many of the design parameters such as speed of traffic, presence of junction and building facades. They are also based on small number of survey sites which represent only a limited number of conditions of built up areas.

At present most of the available Prediction techniques for free and non-free flowing (inspite of limitation for non-free flowing) fall into two categories depending on whether they calculate L_{10} or Leq dB(A), (5 and 6). In Great Britain L_{10} (L_{10} is the sound level exceeded for 10% of the time) has been adopted by the government since it showed satisfactory correlation with human dissatisfaction. Leq, the equivalent sound level is recommended by ISO and it has been found favourable in Europe(7), but as yet it has not been widely used in Britain for traffic noise measurements. In order to adopt a unified scale, the British Noise Advisory Council recommended a gradual transition to the use of Leq for quantification of the noise environment due to each source and also from all sources together(6).

This paper aims to develop comprehensive methods to assess and predict traffic noise in built-up areas under various conditions, for planning purposes as well as to test the validity of Leq dB(A) in the British climate. The work described in this paper forms part of a research project concerning noise from non-free flowing traffic at Bath University (8,9 and 10).

EXPERIMENTAL PROCEDURE

The measurements of road traffic noise were made at 204 sites (172 urban and 32 suburban), in Bath, which satisfied wide variety of conditions as follows:

1. The roads were level and dry.

2. Sites were required which would be typical of non-free flowing traffic and would be at varying distances from a roundabout, an intersection controlled by traffic lights or a priority junction.

3. The surrounding structure was typical of built-up situations. The buildings flanking the roads were continuous on both sides while the study area covered different land uses such as: residential, shopping, offices, open space, urban main routes and principal suburban routes.

4. The measurement positions were at one metre from the nearest kerbside.

5. The measurements of noise levels were sampled hourly (30-minutes per hour) at each site between 7.00 and 19.00 hours and then analysed to give L10, L50 and L90 and Leq dB(A). Other variables of interest were also recorded simultaneously.

MODEL DEVELOPMENT

For practical design purposes three models for determining traffic noise in terms of different factors and circumstances were established. These may be classified as follows:

Urban Model. Urban road networks can be considered to fall into two areas (11): those concerned with junctions (node) and those concerned with the stretch of road between junctions (link). Road junctions are usually places of high congestion as well as of environmental noise. The main reasons are that the vehicles have to decelerate in approaching, stopping and then crossing the junction itself and finally accelerate away to cruising speed once again. This type of vehicle manoeuvre, usually operated through areas surrounded by buildings with a high density of inhabitants, increases the noise level significantly. Investigation of Leq dB(A) in terms of the principal variables has shown that:

1. For the stream of traffic travelling at various speeds below limits of 48 km/h, Leq depends on the composition of the traffic. The contribution of medium and heavy vehicles to the level of noise is significant. The level increases as the number of vehicles increase. In this study the traffic flow rates ranged from 260 to 2532, 6 to 474, and 0 to 99(vph) for light, medium and heavy vehicles respectively.

2. Leq levels depend on the distance from various kinds of junctions, road widths, mean speed of traffic and distance of the measurement points from nearside building facades. The level drops with the increasing values of the above variables. The best final model to fit the data from 172 urban locations was found to be:

$$Leq = 53.2 - 6.00\ lgV + 11.7\ lg(L+6M+10H) - 4.50\ lgW - 0.0107\ J - 5.23\ lg(d-1) \quad .....(1)$$

Where V is the mean speed in km/h. L,M and H in vph are the numbers of light, medium and heavy vehicles respectively (12). W is the road width (m), J is the distance from junctions (m) and d is the distance between nearside kerb and the nearside building facade (m). W, J and d ranged from 6 to 18m, 4 to 327m, and 3 to 25m respectively. The model gave a good correlation with correlation coefficient, R = 0.977, standard deviation σ = 0.688 and accuracy of prediction with $\pm$ 2.2 dB(A). (The L_{10} prediction model developed by the author in the same manner gave R= 0.984, σ = 0.585 and accuracy of prediction with $\pm$1.4dB(A)). The model includes the most significant design parameters and is a practical means for urban planning and environmental assessment.

Sub-Urban and Urban Model. It was decided to devise another prediction model for different conditions and design parameters. Thus, 32 sub-urban sites were studied. The speed was up to 75km/h, despite the sub-urban speed limit of 64km/h, the distance from junctions was extended to 420m and the farside building location was considered. With regard to these conditions the following facts emerged

1. The traffic flow and percentage of heavy and medium vehicles (ranging from 0 to 20%) were found to play an important part. Leq levels increase with the increasing value of these variables.

2. Leq levels depend on the distance from far and nearside building facades. The levels decrease with the increasing values of the variables.
   The model which was found to correlate well with the data from the whole 204 sites is as follows :

$$Leq = 56.5 - 6.53 \lg V + 11.6 \lg Q + 0.172 P - 6.48 \lg F - 0.0098 J - 2.47 \lg N \quad .....(2)$$

Where Q is the mean flow of traffic (ranged from 284 to 3000 vph.), P is the percentage of heavy and medium vehicles, F is the distance between measurement point and farside building facade (ranging from 9.35 to 37.5m), and N is the distance between measurement point and nearside building facade (ranging from 1.5 to 24m). The model showed a high correlation R = 0.960, σ = 0.864 and accuracy within $\pm$ 2.5 dB(A). (Similarly L_{10} prediction model which was developed by the author (10) gave R = 0.969, σ = 0.770 and accuracy with $\pm$ 1.8dB(A)). This model is also comprehensive and provides the planner with another tool based on fundamental parameters.

Relationship Between Leq and L_{10}, L_{50}, L_{90}. In Great Britain the following relation was issued for noise from freely flowing traffic (13): $Leq=L_{50}+(L_{10}-L_{90})^2/56$. Of course, the structure of this model is dependent on the method used and the circumstances of freely flowing traffic. Therefore, the following modification was made for the above relation in connection with noise from non-free flowing traffic in built-up areas, based on 204 urban and suburban positions:

$$Leq = 0.968\, L_{50} + 0.436\, (L_{10}-L_{90}) \quad .....(3)$$

Where L_{50} the sound level exceeded for 50% of the time and L_{90} is the level exceeded for 90% of the time. The model shows accuracy with $\pm$ 2.4 dBA, R = 0.974 and σ = 0.723.

SUMMARY

In view of the British Noise Advisory Council recommendation for a gradual transition to the use of Leq, and the need for forecasting models to assess the effect of traffic noise in built up environments, three Prediction Models to be used for the planning objective were introduced. They were based on a wide range of field measurements at 204 urban and suburban sites. The models represent most of the possible situations, and are accurate and include the fundamental design parameters. In spite of these advantages, the models provide accuracy a little less than those obtained by the author from similar L_{10} models. For urban models the L10 accuracy of prediction was $\pm$ 1.4 dB(A) while Leq gave $\pm$ 2.2. The suburban and urban models gave accuracy of $\pm$ 1.8 dB(A) from L10 model and $\pm$ 2.5 from Leq model.

However, these Leq models are a step forward in understanding Leq, as a design parameter associated with stop-start traffic, which is usually surrounded by a high density of inhabitants. The great deal of attention which was paid to free flowing traffic conditions limited the value of comparisons with other models at this stage. The models were modified to be included in computer techniques which were designed to predict noise levels under a variety of conditions (14 and 15).

ACKNOWLEDGEMENTS

I would like to acknowledge the help and assistance that I have received from Dr. D. J. Croome (Reader) and Mr. W. Powell (Senior Research Fellow) of the School of Architecture and Building Engineering, University of Bath. Thanks are also due to Professor E. Happold (Head of School) and Professor M. Brawne and their staff in the School of Architecture and Building Engineering for their assistance during the period of study.

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Appendix D7

'Traffic Noise Annoyance Near Road Junctions'.

FASE '86, Hungary, 1986.

ABSTRACT

Urban road networks can be grouped into two main types: Those concerned with junctions and those concerned with the stretch of road between junctions. Road junctions are usually places of both a high degree of congestion and of environmental noise. This study investigates the effects of traffic noise experienced by people near a variety of road junctions by combining the use of social and physical surveys. A wide range of field studies were completed at sites selected to represent 39 junctions. The sites were alongside the accelerating and decelerating streams of traffic at positions where the traffic joined traffic lights, roundabouts or priority junctions and extended for an appropriate distance from the junctions. Sites were also chosen to represent different types of land use and traffic conditions. Traffic noise was measured for 12 or 18 hours. A questionnaire consisted of items concerned with the attitude of the public toward noise, along with various urban parameters, and used a 5 point scale. Correlation coefficients were obtained between noise indices and the individual dissatisfaction scores. The interaction between noise indices as well as between interview response items was established. The influence of various kinds of junctions was found for positions within a distance of 240m from the junctions. The proposed paper will deal with the validity of the study.

Appendix D8

Proceedings of The Institute of Acoustics

SOCIAL RESPONSE TO NOISE FROM INTERRUPTED TRAFFIC FLOW

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After nearly a century of motor car travel there remain considerable pressures on the road transport system. Every activity, such as industry, commerce, education and leisure depends on the movement of goods and people consequently the number of road vehicles is now increasing(1). Traffic environmental issues have accompanied growth in the transportation industry. Motor vehicles do have drawbacks because of noise, air pollution,visual effects and accidents. Traffic noise is one of the significant problems facing the modern society. It continues to increase and this growth has led to an increase in noise levels alongside urban roads and motorways to a point where a greater proportion of the population is disturbed(2).

The influence of traffic noise on the environment and on people's health is evident(3 and 4). This is particularly true of urban traffic noise which accompanies the people in their daily activity outdoors and at home. Noise in built-up areas is completely different from that generated by motorway operation, aircraft and railways. Urban noise is emitted from road networks surrounded by buildings and a high density of inhabitants, while other noise affects only specific land use. Under urban conditions the vehicles follow specific driving needs such as decelerating, stopping and accelerating which predominate at traffic lights, roundabouts and priority junctions and constitute important factors in any urban road design in contrast to the steady continuous speed situation for motorways(5).

A road vehicle is defined as a complex source composed of several elementary sources such as the engine(6). It was concluded(7) that in urban traffic, vehicle engine is the main source of noise but manoeuvres, accelerating and decelerating of vehicles and the percentage of heavy goods vehicles has a great influence on the level of noise.

Noise exposure in urban society depends upon many variables, such as traffic flow and speed, distance from noise sources, the sound insulation of facades with windows that are open or shut, road layout, and the presence of intersections(3). In addition, the relative importance of these factors will be different for each building, depending on the building location,design and use(8 and 9).

People's response to road traffic noise is shown in several ways such as: expression of annoyance, difficulty in communications, interference with sleep, degradation of task performance and physiological damage such as noise induced hearing loss(10). With the growing urbanisation and widespread motor vehicles, there is growing awareness by the public of the drawbacks of vehicular traffic, bringing about increased pressures on highway engineers and planners to take account of the environmental issues.

A traffic noise study has been carried out in the City of Bath, which incorporated 244 urban and suburban sites. The investigation considered the variables associated with noise levels from non-free flowing traffic. Prediction models have been developed. The Bath survey has provided an opportunity to study social response to traffic noise and other parameters which characterise the urban environment.

A social study was developed to determine the interaction between social responses and noise exposure; the relation of these responses to the urban environment parameters used in planning; and the correlations between interview response items as well as between noise indices.

Physical Measurements

Road traffic is the dominant form of noise in most of Bath. In the study, land uses were covered - residential, shopping, commercial, and main traffic routes. A representative 48 sites were chosen as a sample of traffic conditions (light, medium and heavy)[11], for each of these types of land use. Thirty minute noise level recordings were made hourly at each site between 06.00 and 24.00 hours. Traffic noise was measured as L_{10},L_{50} and L_{90} dB(A)[12]. Traffic variables such as flow, composition and speed, distance between kerb and buildings facades flanking the road, road width and distance to the nearest intersection[13] were recorded.

The Social Survey

The social survey was carried out at the 48 sites where there are already complaints about the effects of road traffic on the community. Sites were alongside the accelerating and decelerating streams of traffic. Traffic lights, roundabouts and junctions at various distances were featured. At each location a sample of 6-12 subjects from properties fronting onto the road were interviewed. The population had to be living or working along the roads and experience the effect of the traffic. The social survey questionnaire consists of: firstly; 32 questions concerning the subjects' attitudes on traffic noise outside and indoors including the roles of types of vehicles, presence of intersections, accelerating of vehicles, brakes, interrupted traffic, window status, sleep disturbance and interference with TV and radio, conversation and concentration. Secondly, 27 questions concerning the areas such as: period of living and working, source of noise and feeling about the area. Thirdly, 6 questions were concerning basic information; fourthly, the second part of the questionnaire was general data filled in by the author who acted as interviewer.

A five point scale was used ranging from (definitely satisfactory, not at all annoyed, never, not at all reduced and not at all noisy) to 5 (definitely unsatisfactory, extremely annoyed, all the time, very much reduced and extremely noisy) for twenty-three items.

The final structure of the questionnaire was adapted from previous experience[14] though significant changes were made for the purpose of this study.

Results

A total of 319 subjects were interviewed with a structured questionnaire. The proportion of female and male were 48.9% and 51.1% respectively. In terms of age characteristics a small percentage of people were over 60 (19.1%). The buildings in the study were mainly terrace, detached or semi-detached and they all had windows on the road facing facade. The percentage of subjects living at the same address less than one year was 12.5%. The predominant source of noise was road traffic noise in all locations. 41.1% of the selected sample live in the main route area where heavy traffic conditions were prevalent.

The average values of nineteen response items were 15.1% at point 2 (minimum) and 27.86% at the highest point of the 5 point scale (maximum). Figures 1 and 2 illustrate envelopes showing range of disturbance responses and response to different sources respectively.

34.2% selected the middle point of the 5 point response scale when they were asked to indicate whether or not they noticed the noise inside their buildings. Figure 3 shows the relationship between people's responses indoors and outdoors and noise level. All main route subjects found the medium and heavy goods vehicles very annoying. The highest motorcycle score was 29.5% at number four of the five point response scale. Figure 4 explains the interaction between noise level L_{10} dB(A) and people's response to different types of vehicles.

The survey indicated that most of the noise nuisance resulted from vehicle manoeuvres but traffic lights, roundabouts and priority junctions were mentioned by 84.7%. The main factor associated with intersection is the distance of the range of influence. The main people responses were found for sites within 240 m from different kinds of intersections. Figure 5 shows the correlation between people's response to noise from intersections and vehicle manoeuvre and distance.

68.7% of subjects reported that they keep their windows shut all the time (number 5 on the scale), while 78.4% mentioned sleep disturbance (Figure 6). 32% of subjects felt that noise was reducing the financial value of their property and chose the highest point of the scale. 87% mentioned the financial effect at a different level.

The survey indicated that the most acceptable level was L_{10} = 68 dB(A) corresponding to number 2 of judgement of the five point response scale. The results also show the different sensitivities for each situation as depicted by the change of slopes on Figures 3-6.

Conclusions

Significant correlation was found between noise level L_{10} dB(A) and social response, the noise from light, medium and heavy goods vehicles at traffic lights, roundabouts and priority junctions besides vehicles accelerating and decelerating. Interactions also exist between social responses and urban environmental variables such as distance. The influence of different kinds of intersections was found for positions within a distance of 240 m. The influence of noise exposure on disturbing people during sleep, conversation or watching television has been established.

The level of L_{10} = 68 dB(A) at number 2 of the 5 point response scale was found to be the most acceptable level associated with people's response to traffic noise exposure in this survey. A high percentage of subjects felt that noise was reducing the financial value of their property.

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I would like to acknowledge the help and assistance that I have received from Dr. D. J. Croome (Reader) and Mr. W. Powell of the School of Architecture and Building Engineering, Bath University. Thanks are also due to Professor M. Brawne and Professor E. Happold and their staff in the School of Architecture and Building Engineering for their assistance during the period of study. I would also like to thank Mr. D. Clark of Bath University Computer Unit, Dr A. Lewis of the School of Humanities and Social Sciences, Mr. G. Vulkan of Greater London Council, Dr. D. Gilbert of Imperial College, Mr J. Sargent of the Building Research Station and Dr. P. Nelson of Transport and Road Research Laboratory for

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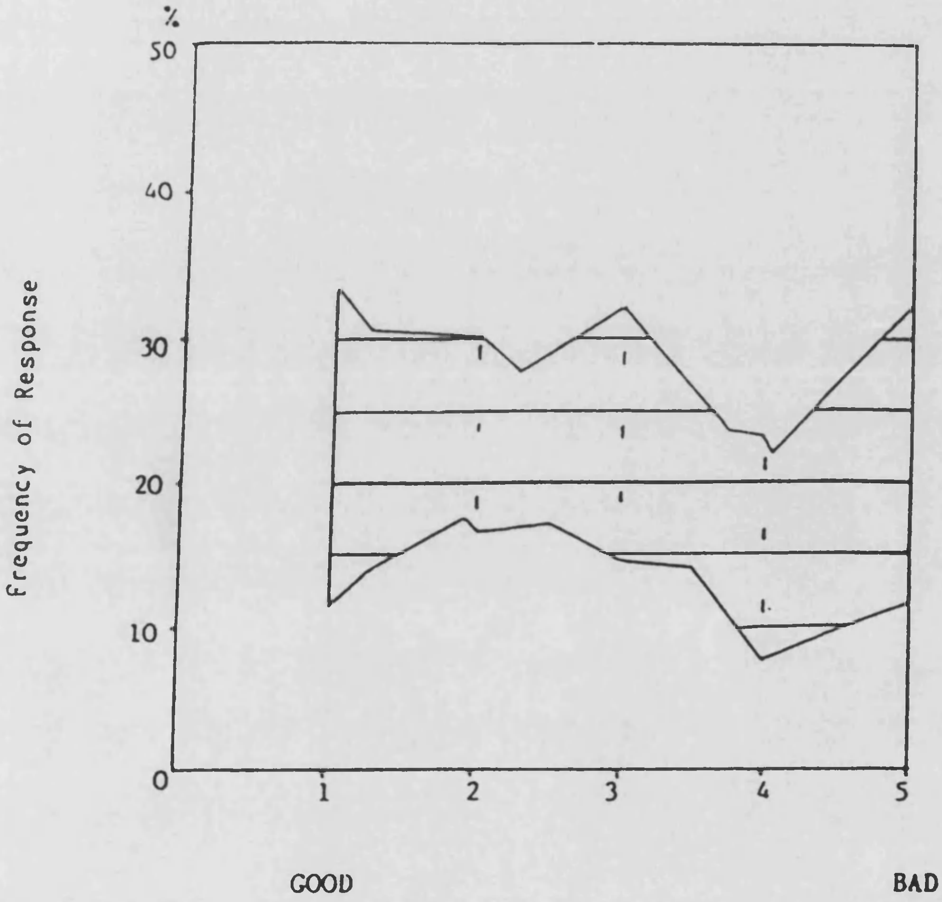

Figure 1 Envelopes showing range of disturbance response to: sleep, concentration, TV and radio, conversation, vibration, bedroom position and reduction of the financial value of the property.

SOCIAL RESPONSE TO NOISE FROM INTERRUPTED TRAFFIC FLOW

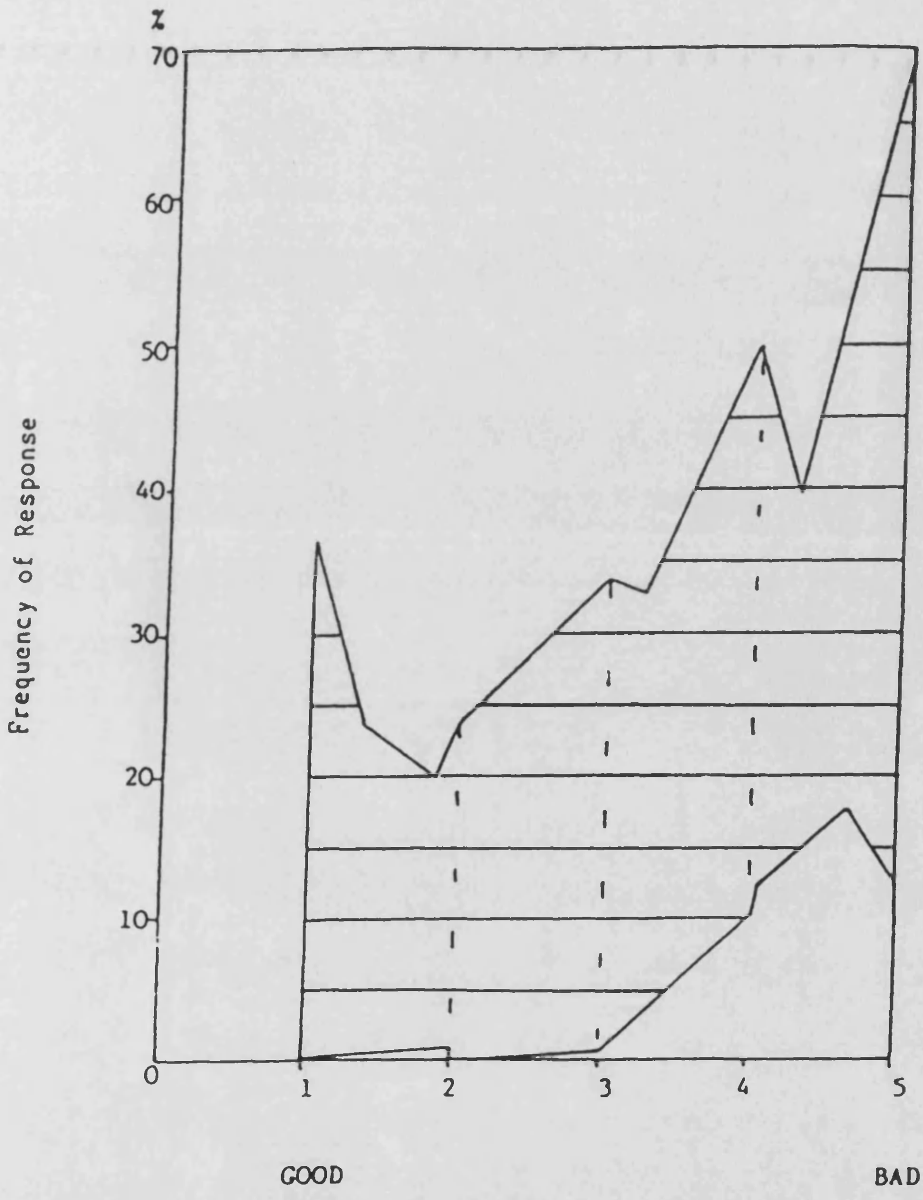

Figure 2 Response to different sources such as: outside and indoor noise, cars, buses, heavy lorries, intersection noise, squealing tyres, motorcycles, acclerating vehicles, closed windows and interrupted traffic.

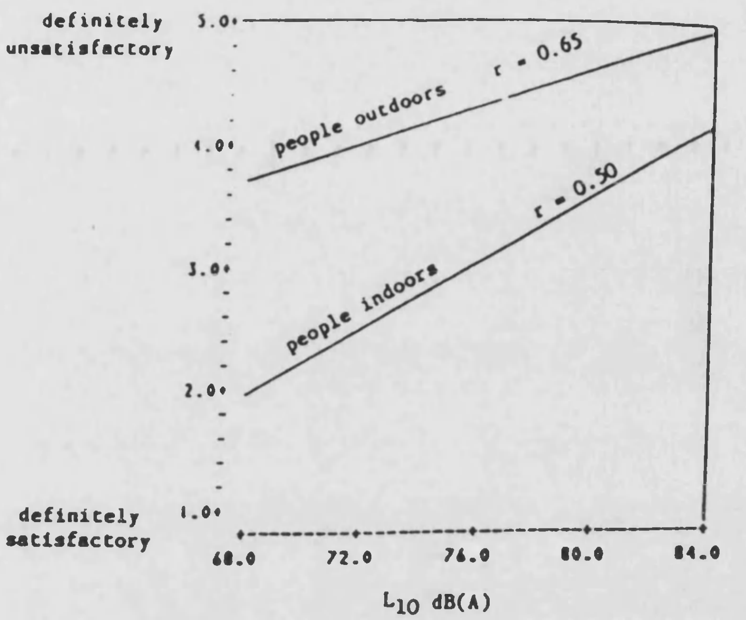

Figure 3 Noise Level and people's response to indoor and outdoor noise.

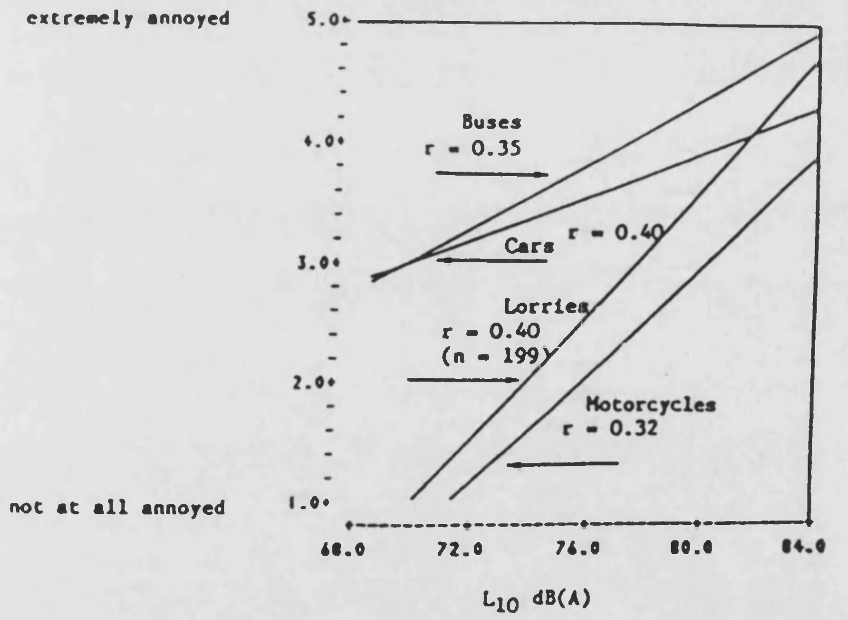

Figure 4 Noise level and people's response to different kinds of vehicle relationships.

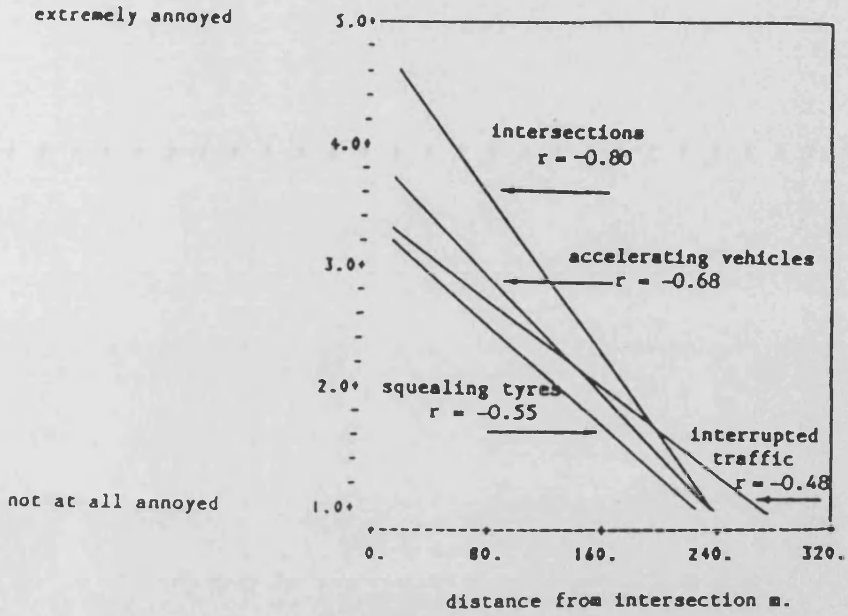

Figure 5 The interaction between people's response to different noise factors and distance.

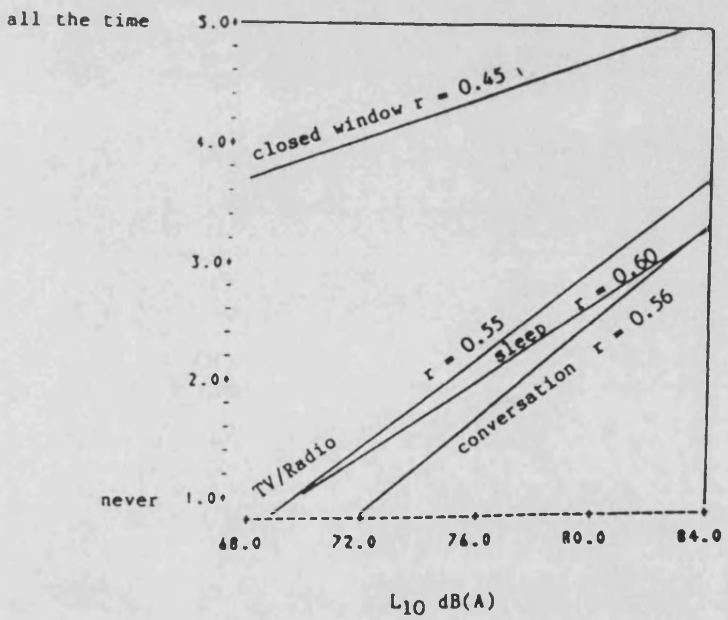

Figure 6 Noise level and people's disturbance response relationships.

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Appendix D9

URBAN ROAD TRAFFIC - NOISE LEVEL PREDICTION

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ENGLAND

ABSTRACT

Most prediction techniques in current use for road traffic noise are based on smooth flowing traffic. Attempts to provide prediction equations for noise levels from interrupted traffic flow conditions, normally encountered in urban situation, too often result in equations that are complex for practical use or give unacceptable errors in the simplified forms. This study sets out to use noise, road and traffic parameters familiar to designers and planners and to give an accuracy of prediction to within ± 1 dB(A).

INTRODUCTION

The City of Bath has a population of 80,000 and, as with most modern cities, marriage of the motor vehicle with other interests provide for a great deal of conflict, specially since Bath is one of the most beautiful cities in Europe with powerful and vociferous conservation lobbies. As well as architectural there are topographic constraints, since Bath is surrounded by hills, which inhibit planning and control of road traffic. In the late 1960s radical schemes such as the road tunnel through the heart of the City were proposed by Buchanan (1) in order to preserve the Georgian character of Bath and defend against the effects of funnelling heavy traffic through the City.

Noise from road traffic is the dominant form of noise in most of Bath and the variety of traffic conditions make it a most useful base for studies into urban traffic noise. The main types of traffic in the City can be considered as

1. Heavy traffic conditions: such as on main routes which enable traffic to enter or leave the City.

2. Medium traffic conditions: such as in office, shopping and some residential areas.

3. Light traffic conditions: such as in residential and open space areas.

172 sites were chosen in this study to give representative samples of traffic conditions.

SITES

Sites were chosen near roundabouts, traffic light intersections and priority junctions. Noise levels were recorded at varying distances from each node, up to a maximum distance of 350 m. - intersections are referred to as nodes and the stretches of road between nodes as links (2). Thirty minute recordings were made hourly between 07.00 and 19.00 hours and then analysed (3) to provide L_1, L_{10}, L_{50}, L_{90} and L_{EQ} values. Traffic volume, composition and speed were also recorded, as was road width, distance between kerb and received, distance between kerb and building facades flanking the road and distance to nearest node. Road surfaces were dry asphalt and, at this stage of the study, with no gradient.

TRAFFIC VARIABLES

Traffic flow, depending on location and time, range from 284 to 2730 veh./hr. and was divided for the purpose of the study into three classes (4)

1. Cars, vans and light goods vehicles <3000 kg unladen weight

2. Medium goods vehicles with two axles > 3000 kg unladen weight, including buses and coaches.

3. Heavy goods vehicles, which include all commercial vehicles with three or more axles.

A speed restriction of 48 Km/hr existed at all sites, but speed measured ranged from 12 to 57 Km/hr. With other variables constant noise associated with increasing speed from 24 Km/hr to 48 Km/hr was investigated. The use of gear selection was dominant(5) and therefore unlike free flowing traffic where noise levels increase with the speed of the behicles, noise levels decrease for urban traffic as speed of vehicle increases.

Road widths ranged from 6 to 18m; distances from kerb to nearside building facades ranged from 2m to 24m; whilst the distance between kerb and receiver were kept at 1m with a microphone height of 1.2m. Distance to nearest node ranged from 4m to 327m.

PREDICTION MODEL

Using multiple regression analysis, equations were derived for L_{10}, L_{EQ} and combinations of L_1, L_{10}, L_{50} and L_{90}. In the United Kingdom, L_{10} is the basis for numerous standard fixing limits dealing with road traffic noise, (3) (6), although L_{EQ} is often used in other European countries. The original equation derived for L_{10} was

$$L_{10} = 54.8 - 5.57 \log V - 4.17 \log W - 0.0116J + 12 \log (L + 6M + 10H) - 5.26 \log (d - k) \text{ dB(A)}$$

where V is the mean vehicle speed (Km/hr)

W is the road width (m)

J is the distance from the nearest node (m)

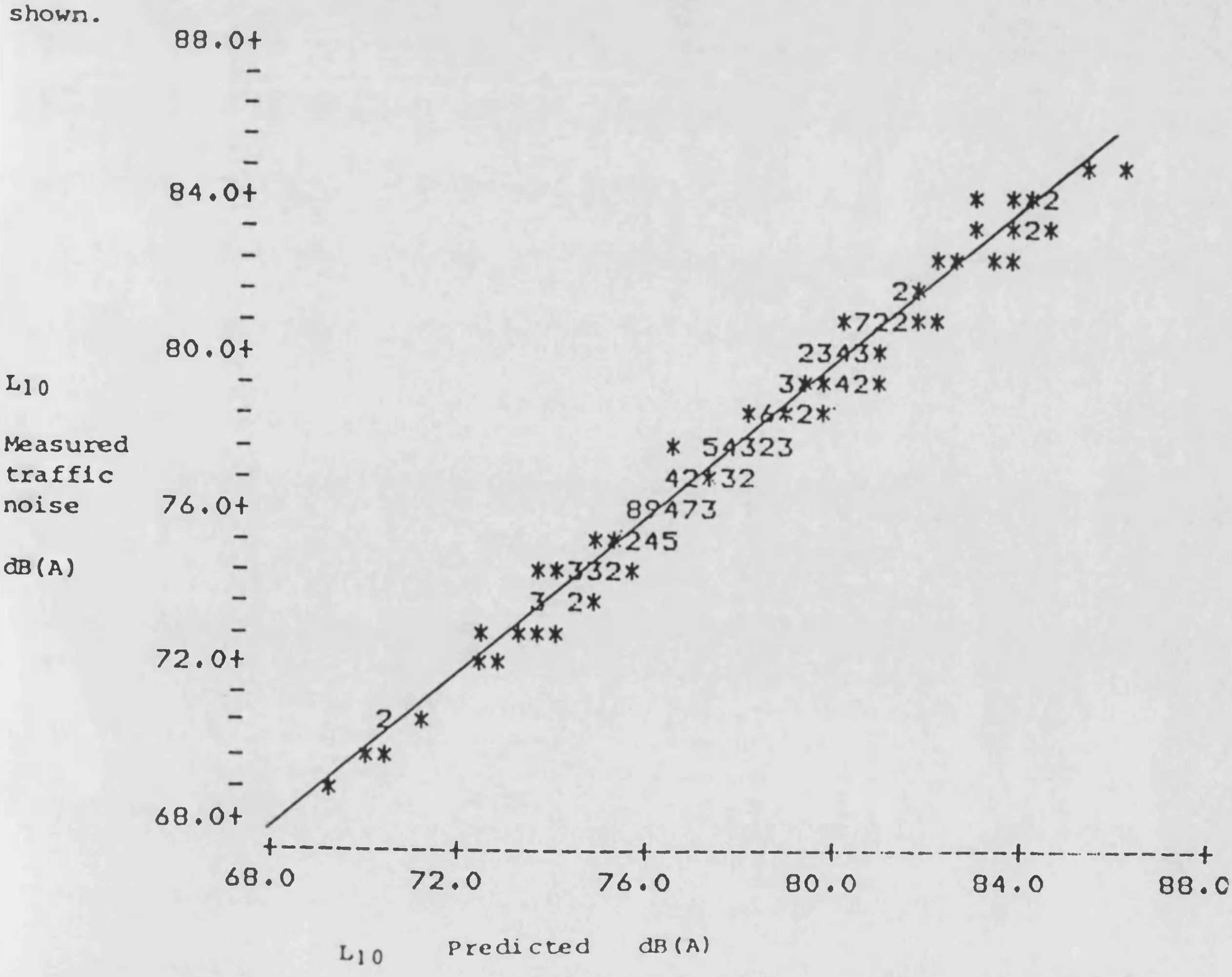
L, M and H are the number of light, medium and heavy goods vehicles (Veh/hr).

D is the distance between kerb and nearside facade (m)

K = 1 is the distance between kerb and receiver (m)

This equation gave a correlated R = 0.984, standard deviation 0.585 and and residual ± 1.

Comparison of the predicted and measured traffic noise levels are shown.



The relevance of effects due to considering farside building facades and a more general form of the equation to include gradient, is still being investigated. Questionnaires are also now being distributed to residents in the vicinity of each site and should provide additional information for this paper when presented in August 1984. Equations using L_{EQ} and simplified forms for L_{10} will also be discussed.

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